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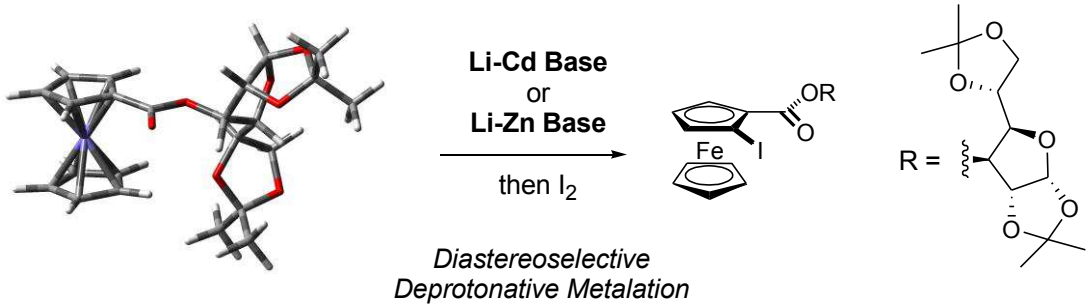
Graphical Abstract



Diastereoselective deprotonative metalation of chiral ferrocene derived acetals and esters using mixed lithium-cadmium and lithium-zinc combinations

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Abstract:

In situ bimetal combinations, and notably those prepared from MCl_2(·TMEDA) (M = Zn, Cd; TMEDA = *N*,*N*,*N*′,*N*′-tetramethylethylenediamine) and Li(TMP) (3 or 4 equiv, TMP = 2,2,6,6-tetramethylpiperidino), were screened for their ability to diastereoselectively deprotonate ferrocenes bearing a chiral group. The ferrocene carboxylate generated from diacetone-D-glucose afforded the corresponding 2-iodo derivative in 74% yield with 90% de (S_P diastereoisomer) using the base generated from $CdCl_2$ and Li(TMP) (3 equiv), and in 85% yield with 91% de (S_P diastereoisomer) through a double asymmetric induction using a chiral lithium-zinc base generated from $ZnCl_2$·TMEDA and lithium (*R*)-bis(1-phenylethyl)amide (4 equiv). In contrast, using a combination prepared from $ZnCl_2$ and Li(TMP) (4 equiv) with the ferrocene carboxylate obtained from 6-(*tert*-butoxycarbonylamino)-6-deoxy-3-*O*-methyl-1,2-*O*-isopropylidene-α-D-glucofuranose led to the R_P-iodo derivative in 57% yield after separation. Suzuki coupling was performed satisfactorily on the isolated S_P and R_P diastereoisomer iodoesters.

1. Introduction

Metalation of aromatic compounds is traditionally performed using lithium bases in the presence of Lewis bases that simplify their aggregation state (e.g. tetrahydrofuran (THF) as solvent or *N*,*N*,*N*′,*N*′-tetramethylethylenediamine (TMEDA) as additive).[1] Nevertheless, polar carbon-lithium bonds are hardly compatible with substrates bearing reactive functions (esters, nitriles…) and π-deficient heterocycles. As a consequence, when these sensitive aromatic compounds are submitted to conventional lithium bases in deprotonation reactions, very low temperatures and/or the presence of an in situ electrophile are required.[1] By changing lithium with magnesium, the chemoselectivity of the reactions can be improved, but to the detriment of the efficiency since a large excess of base has to be used due to its reduced reactivity.[2]

Activation of lithium bases by metal additives in order to obtain more efficient and/or more chemoselective deprotonation reactions is a challenging field, and many $[(R)_n(R')_{n'}MLi]$-type

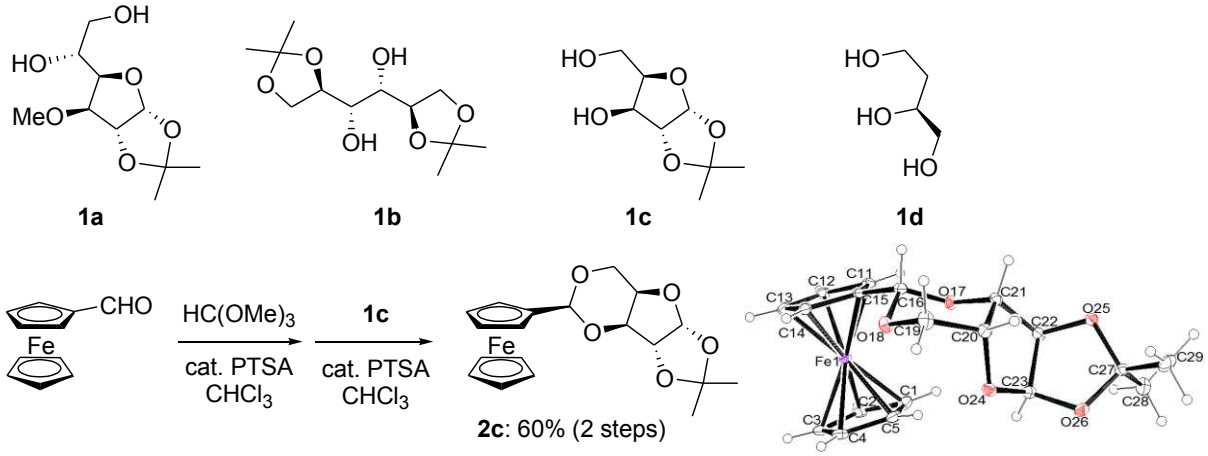
superbases (M = metal; R, R' = alkyl, amino, chloro…) have already been reported.[3] Mixtures of organolithiums and M alkali metal alkoxides were the first to be developed; well-known examples are LIC-KOR (LIC = butyllithium, KOR = potassium *tert*-butoxide)[4] and BuLi-Li(DMAE) (DMAE = 2-dimethylaminoethoxide).[5] Later, the synergy exhibited by merging lithium compounds with softer non-alkali derivatives significantly pushed the limits of aromatic deprotonative metalation to new heights. Indeed, $[(R)_n(R')_{n'}MLi]$-type compounds with M different from an alkali metal displayed a large panel of reactivities, depending on both the metal M and its ligands; in particular, TMP-containing combinations (TMP = 2,2,6,6-tetramethylpiperidino) were identified as useful bases to perform the aromatic functionalization of a large range of substrates.[6]

Within this framework, we developed pairs of metal amides which complement each other in deproto-metalation reactions. In particular, the TMP-based lithium-zinc[7] and lithium-cadmium mixtures,[8] respectively prepared from $ZnCl_2 \cdot$TMEDA and $CdCl_2 \cdot$TMEDA, and Li(TMP) (3 equiv), were identified as suitable reagents to chemoselectively functionalize a variety of aromatics. Due to the importance of ferrocenes for applications ranging from catalysis[9] to materials science[10] and bioorganometallic chemistry,[11] such base combinations were also successfully applied to the functionalization of acetal- and ester-substituted derivatives through room temperature metalation-iodination sequences.[7d,12]

The presence of a heteroatom-containing substituent on ferrocene usually directs lithiation to the adjacent position, affording 1,2-unsymmetrical derivatives upon quenching with electrophiles. Suitable chiral groups were early identified in order to control the absolute planar chiral configuration in the course of such reactions.[13] We recently communicated diastereoselective deproto-metalation reactions starting from chiral ferrocene esters using these mixed lithium-zinc[14] and lithium-cadmium[15] bases. Herein, the details of our investigations on sugar-based ferrocene acetals and esters are recorded.

2. Results and Discussion

Chiral acetals being described as suitable functions to induce diastereoselective lithiation of the corresponding ferrocenes,[16] we first considered such substrates to evaluate our basic combinations. Accordingly, the synthesis of the chiral ferrocene acetals derived from the commercially available 1,2-*O*-isopropylidene-3-*O*-methyl-α-D-glucofuranose (**1a**), 1,2:5,6-di-*O*-isopropylidene-D-mannitol (**1b**), and 1,2-*O*-isopropylidene-α-D-xylofuranose (**1c**) diols was undertaken first. The reactions were carried out with ferrocene dimethylacetal in chloroform, using *p*-toluenesulfonic acid as catalyst.[16a] Whereas the transacetalization using the diols **1a**,**b** gave diastereoisomeric mixtures, a single compound **2c** was obtained using the diol **1c**, and was characterized unambiguously by X-ray diffraction (Scheme 1).

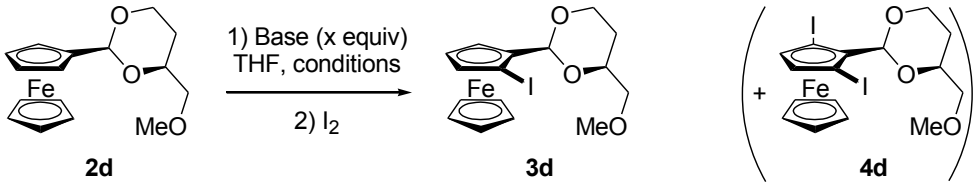


Scheme 1. Polyols **1a-d**, synthesis of the chiral ferrocene acetal **2c** and ORTEP diagram (30% probability) of the acetal **2c**.

Different reagents were employed in the deprotonation of **2c**, amongst all (i) the all TMP lithium-cadmium combination already identified as being able to perform chemoselective reactions efficiently,[8] (ii) other organolithiums (BuLi, BuLi·TMEDA, ^{s}BuLi, ^{t}BuLi in THF), and (iii) ^{t}BuLi·^{t}BuOK reported as capable of deprotonating bare ferrocene.[17] Unfortunately, whatever the conditions used with the lithium-cadmium base (THF, room temperature or pentane, reflux), with the organolithium compounds (THF, -10 °C to room temperature), and with ^{t}BuLi·^{t}BuOK (THF, -75 to -15 °C), only starting ferrocene, ferrocenecarboxaldehyde (deprotection of the acetal function), and its corresponding addition derivatives were observed after the workup with no deprotonation occurring at all.[18]

Undeterred by these results, we considered the involvement of the Kagan's ferrocene acetal[16a,16c,16s] **2d** (derived from the commercially available triol **1d**) in the deproto-metalation using lithium-zinc and lithium-cadmium combinations (Table 1). Using the base in situ prepared in THF at 0 °C (15 min) from $ZnCl_2$·TMEDA (1 equiv) and Li(TMP) (3 equiv) led, after 2 h at room temperature and subsequent interception with iodine, to the iodide **3d** and the diiodide **4d** in 75 and 15% yield, respectively. Analysis of the iodide **3d** by ^{1}H NMR showed a 69% de, and comparison with previously reported spectral ^{13}C NMR data[16r] allowed the main diastereoisomer to be identified as $\boldsymbol{S_P}$ (entry 1). The base employed being a 1:1 mixture of $Zn(TMP)_2$ and Li(TMP),[7i] the sequential addition to the substrate **2d** of a THF solution of $ZnCl_2$·TMEDA (1 equiv) and Li(TMP) (2 equiv) and, 30 min later, a THF solution of Li(TMP) (1 or 2 equiv) at -30 °C was attempted. After 2 h stirring at this temperature and iodolysis, no diiodide was observed but a mixture of the iodide **3d** (37 or 45% yield, respectively) with starting material **2d** (35 or 27%). Under these conditions, the de, still in favor of the S_P diastereoisomer, was slightly improved to reach 76 or 79%, respectively (entries 2 and 3).

Table 1. Metalation of the Kagan's ferrocene acetal **2d** using lithium-zinc and lithium-cadmium combinations followed by trapping with I_2.



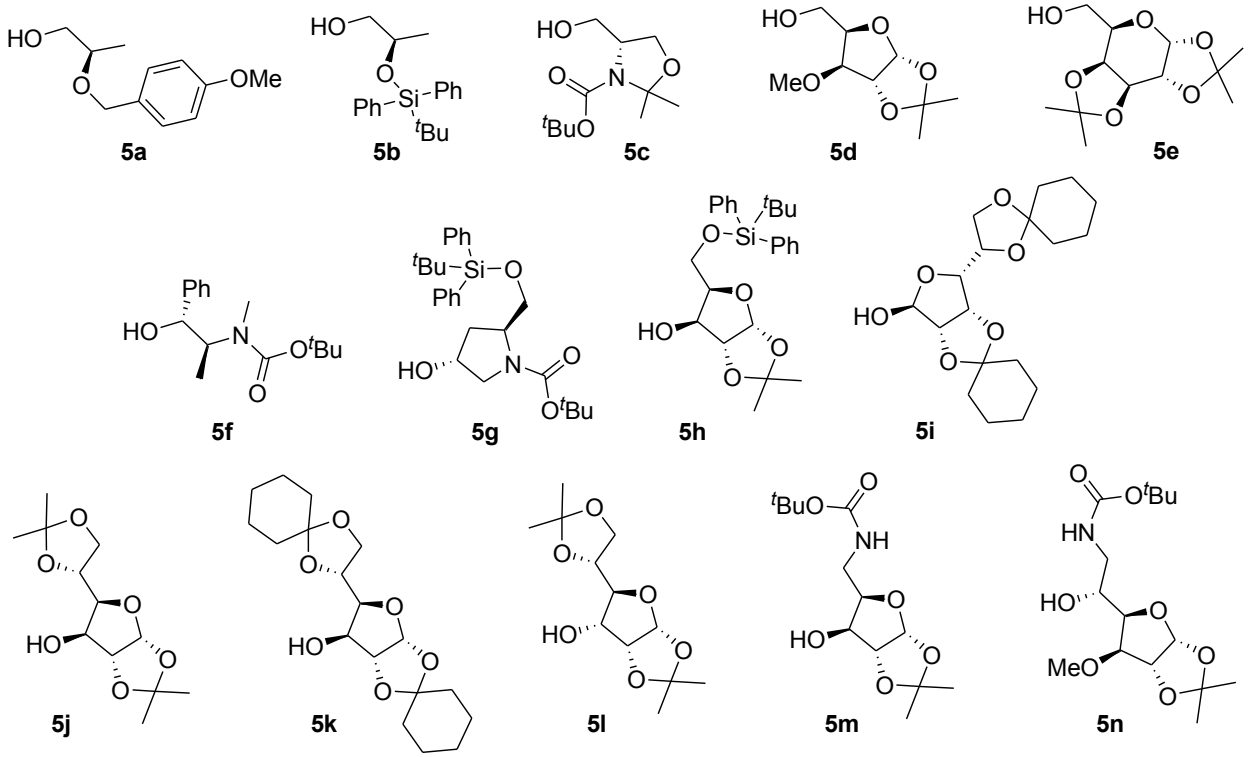
2d **3d** **4d**

Entry	Base (x equiv)	Conditions	Yield of **3d** (%)	Yield of **4d** (%)	de (%)[a]
1	$ZnCl_2$·TMEDA (1) + Li(TMP) (3)	rt, 2 h	75	15	69 (S_P)[b]
2	$ZnCl_2$·TMEDA (1) + Li(TMP) (2) and, 30 min later, Li(TMP) (1)	-30 °C, 2 h	37[c,d]	0	76 (S_P)[b]
3	$ZnCl_2$·TMEDA (1) + Li(TMP) (2) and, 30 min later, Li(TMP) (2)	-30 °C, 2 h	45[e,d]	0	79 (S_P)[b]
4	$CdCl_2$·TMEDA (1) + Li(TMP) (3)	rt, 2 h	0	79	
5	$CdCl_2$·TMEDA (0.5) + Li(TMP) (1.5)	rt, 2 h	41[f,d]	0	71 (S_P)[b]

[a] Determined from the integration of the ^{1}H NMR spectrum of the crude mixture (signals at 5.41 and 5.38 ppm in $CDCl_3$ or at 5.45 and 5.42 ppm in C_6D_6) for the S_P and R_P diastereoisomer, respectively).
[b] The attribution of the configuration was made on the basis of previously reported data.[16r]
[c] 35% of **2d** was recovered.
[d] Estimated yield, due to the presence of starting material.
[e] 27% of **2d** was recovered.
[f] 53% of **2d** was recovered.

Using the corresponding lithium-cadmium base, prepared from $CdCl_2$·TMEDA (1 equiv) and Li(TMP) (3 equiv), the diiodide **4d** proved to be the only product formed (entry 4). Reducing the amount of base furnished the monoiodide **3d**, but in moderate yield and de similar to that obtained using the lithium-zinc base (entry 5).

Encouraged by these preliminary results, we decided to consider the use of chiral groups with which monometal lithium bases are not compatible. A literature survey showed that ferrocene chiral esters have never been used for this purpose.[13b,13e] In a previous paper, we reported the possible deprotonative metalation of ferrocene esters using the all TMP lithium-zinc and lithium-cadmium combinations.[7d] Inspired, we turned our attention to the variety of chiral ferrocene esters **6a-n**, prepared from ferrocenecarboxylic acid and the alcohols **5a-n** (Scheme 2) under classical conditions,[19] in order to attempt their diastereoselective deproto-metalation.

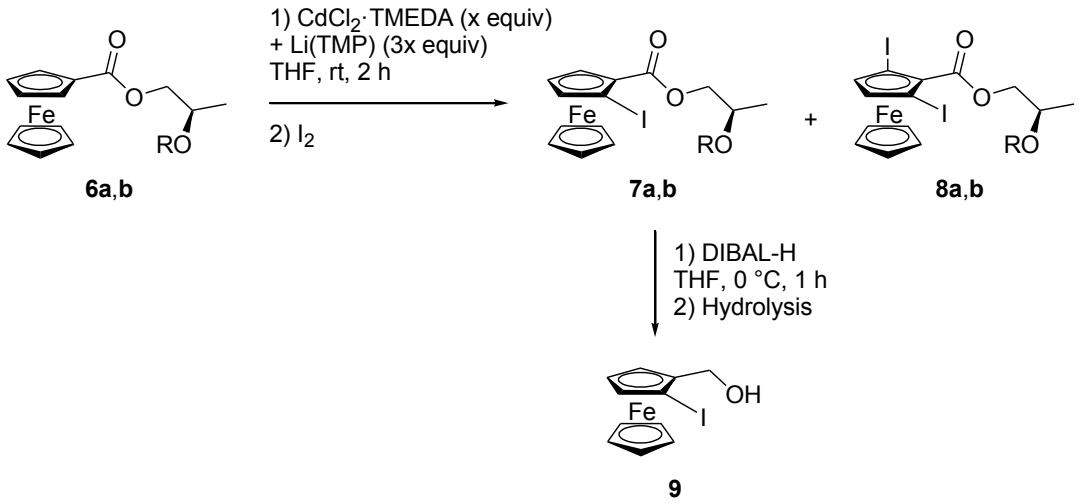


Scheme 2. Chiral alcohols **5** used to prepare the ferrocene esters.

The metalation of PMB- and TBDPS-protected (*R*)-2-hydroxypropyl ferrocenecarboxylate **6a**,**b** was first attempted using the lithium-cadmium base prepared in situ from $CdCl_2$·TMEDA (x equiv) and

Li(TMP) (3x equiv) in THF at room temperature (Table 2). With x = 1, the diiodides **8a**,**b** were formed in low to moderate yields (29 and 68%, respectively, entries 1 and 2). However, reducing the amount of base (x = 0.5) resulted in the formation of the monoiodides **7a**,**b** as major products (entries 3 and 4). Subsequent reduction to 2-iodoferrocenemethanol (**9**) using DIBAL-H,[20] and analysis by HPLC using a chiral stationary phase (AS-H) showed that the metalation was not sufficiently diastereoselective.

Table 2. Metalation of PMB- and TBDPS-protected (*R*)-2-hydroxypropyl ferrocenecarboxylates **6a,b** using the all TMP lithium-cadmium base followed by trapping with I_2.

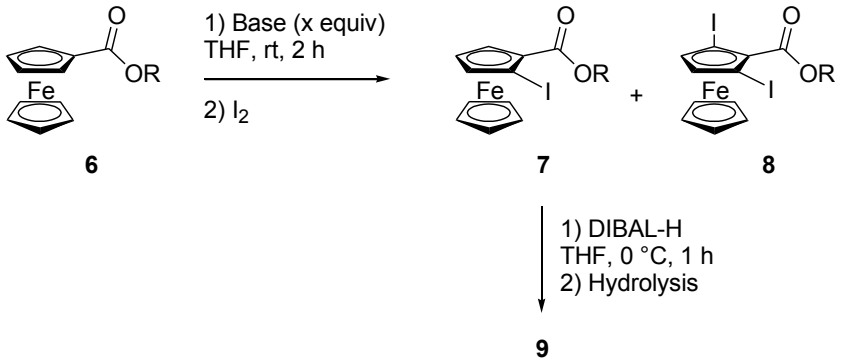


Entry	Substrate	R	x	**7**, Yield (%)	**8**, Yield (%)	Yield (%) for **9**, ee (%)[a]
1	**6a**	PMB	1	**7a**, 35	**8a**, 29	[b]
2	**6b**	TBDPS	1	**7b**, 7	**8b**, 68	[b]
3	**6a**	PMB	0.5	**7a**, 76	**8a**, 7	94, 7 (S_P)[c]
4	**6b**	TBDPS	0.5	**7b**, 54	**8b**, 5	98, 1 (S_P)[c]

[a] Determined by HPLC analysis on a chiral stationary phase (AS-H column, eluent: 9:1 hexane-isopropanol, 1 mL/min, λ = 252 nm).
[b] Reduction not performed.
[c] The attribution of the configuration was made on the basis of previously reported data.[21]

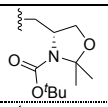
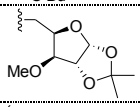
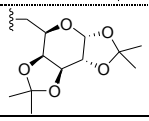
Next, another set of chiral ferrocene esters **6c-e** were taken up for study, prepared from (*R*)-*N*-(*tert*-butoxycarbonyl)-4-(hydroxymethyl)-2,2-dimethyloxazolidine (**5c**), 1,2-*O*-isopropylidene-3-*O*-methyl-α-D-xylofuranose (**5d**) and 1,2:3,4-di-*O*-isopropylidene-α-D-galactopyranose (**5e**) as primary alcohols, and ferrocenecarboxylic acid under the earlier mentioned conditions. These esters were converted to the corresponding iodo derivatives **7c-e** (Scheme 3, Table 3). While the metalation of **6c** proved difficult, giving only a low yield in the presence of 1 equiv of the lithium-cadmium base (entry 1), that of **6d**,**e** proceeded efficiently using 0.5 equiv of base (entries 2 and 3). As previously observed for **6a**,**b**, even

herein low diastereoselectivities were obtained in favor of the R_P diastereoisomer when **5c** was the chiral alcohol used, and in the favor of the S_P diastereoisomer when **5d**,**e** were the chiral alcohols.



Scheme 3. Metalation of chiral ferrocenecarboxylates **6c-i** using lithium-cadmium or lithium-zinc combination followed by trapping with I_2.

Table 3. Metalation of chiral ferrocenecarboxylates **6c-e** using the base in situ prepared from $CdCl_2 \cdot TMEDA$ (x equiv) and Li(TMP) (3x equiv) followed by trapping with I_2.

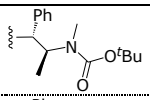
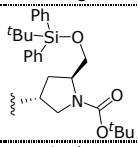
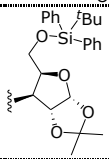
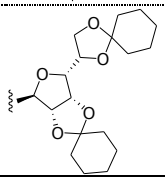
Entry	Substrate, R	x	**7**, Yield (%)	**8**, Yield (%)	Yield (%) for **9**, ee (%)[a]
1	**6c** 	1	**7c**, 18[b]	**8c**, 0	98, 14 (R_P)[c]
2	**6d** 	0.5	**7d**, 92	**8d**, 3	93, 4 (S_P)[c]
3	**6e** 	0.5	**7e**, 82	**8e**, 4	95, 8 (S_P)[c]

[a] Determined by HPLC analysis on a chiral stationary phase (AS-H column, eluent: 9:1 hexane-isopropanol, 1 mL/min, λ = 252 nm).
[b] Estimated yield, due to the presence of starting material.
[c] The attribution of the configuration was made on the basis of previously reported data.[21]

Based on the above results, it was presumed that if the chiral group could be moved closer to the deprotonation site, the ees (des) could be improved; thus, secondary alcohols were next considered (Schemes 2 and 3, Table 4). Toward this purpose, (1*R*,2*S*)-*N*-(*tert*-butoxycarbonyl)ephedrine (**5f**), (2*S*,4*R*)-*tert*-butyl 4-hydroxy-2-(*tert*-butyldiphenylsilyloxymethyl)-1-pyrrolidinecarboxylate (**5g**), 5-*O*-(*tert*-butyldiphenylsilyl)-1,2-*O*-isopropylidene-α-D-xylofuranose (**5h**), and 2,3:5,6-di-O-cyclohexylidene-α-D-mannofuranose (**5i**) were converted to the corresponding ferrocene esters **6f-i** in good yields. When **6f** was consecutively treated by 0.5 equiv of the lithium-cadmium base and then iodine as before, the iodo ester **7f** was isolated in 84% yield and an encouraging 30% ee (S_P), as

determined after reduction to 2-iodoferrocenemethanol (**9**) (entry 1). Both the all TMP lithium-cadmium and lithium-zinc bases were tested for the functionalization of the other esters; starting from **6g**, no reaction was noted upon contact with the lithium-cadmium base (entries 2 and 3). However, under the same reaction conditions, the use of the lithium-zinc base afforded the expected derivative **6g** in 73% yield (entry 4). The reactions from **6f** and **6g** proceeded with similar diastereoselectivities (entries 1 and 4). Compound **6h** was readily metalated using either 0.5 equiv of the lithium-cadmium base or 1 equiv of the lithium-zinc base; the R_P diastereoisomer was formed predominantly (20% de, entries 5 and 6). Concerning **6i**, the metalation was not complete even with both kinds of base, and low to significant des were obtained in favor of the S_P (entries 7-9). It is pertinent to mention that it was possible to avoid the competitive dideprotonation reaction by modifying the R group of the ester, and that using excess of base could improve the diastereoselectivity (compare entries 7 and 8).

Table 4. Metalation of chiral ferrocenecarboxylates **6f-i** using the bases in situ prepared from $MCl_2 \cdot TMEDA$ (x equiv) and Li(TMP) (3x equiv) followed by trapping with I_2.

Entry	Substrate, R	M, x	**7**, Yield (%), de (%)[a]	Yield (%) for **9**, ee (%)[b]
1	**6f** 	Cd, 0.5	**7f**, 84[c]	93, 30 (S_P)[d]
2	**6g** 	Cd, 0.5	[e]	
3		Cd, 1	[e]	
4		Zn, 1	**7g**, 73	94, 33 (S_P)[d]
5	**6h** 	Cd, 0.5	**7h**, 78, 20	50, 22 (R_P)[d]
6		Zn, 1	**7h**, 86, 20	61, 22 (R_P)[d]
7	**6i** 	Cd, 1	**7i**, 38[f], 27	(S_P)[d,g]
8		Cd, 1.5	**7i**, 67[f], 48	(S_P)[d,g]
9		Zn, 1	**7i**, 50[f], 17	(S_P)[d,g]

[a] When possible, determined from the integration of the ^1H NMR spectrum of the crude mixture.
[b] Determined by HPLC analysis on a chiral stationary phase (AS-H column, eluent: 9:1 hexane-isopropanol, 1 mL/min, $\lambda = 252$ nm).
[c] The diiodide **8f** was isolated in 9% yield.
[d] The attribution of the configuration was made on the basis of previously reported data.[21]
[e] No reaction.
[f] Estimated yield, due to the presence of starting material.
[g] Reduction performed on a fraction.

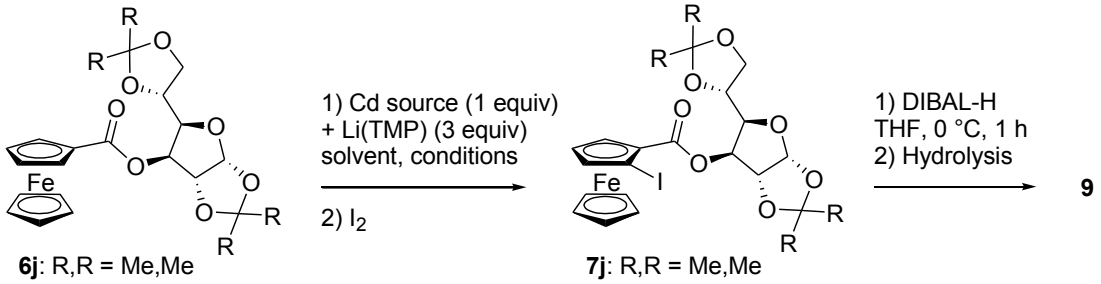
A thorough study was then undertaken in order to evaluate the parameters responsible for the diastereoselectivity with ferrocene carboxylate **6j** derived from inexpensive diacetone-D-glucose (**5j**). Different reaction conditions were employed using lithium-cadmium bases (Table 5). Thus, the first reaction was performed as before using 1 equiv of the all TMP combination to furnish, after interception, the monoiodo derivative **7j** in 85% yield and 74% de (entry 1). Using lower reaction temperatures (entries 2 and 3) or different reaction times (entries 4 and 5) had no effect on the conversion. Concerning the diastereoselectivity, reducing the reaction temperature from room temperature to -20 °C led to a de decreased by about 10% (entry 3). Further, the reaction was performed using different solvents. Et_2O and toluene were first compared with THF; both gave similar yields but lower des (entries 6 and 7). In the absence of LiCl, the reaction carried out in toluene led to a lower conversion (entry 8). On the contrary, the reaction proved more efficient in the presence of TMEDA (5 equiv, 91% yield), but to the detriment of the diastereoselectivity (54% de, entry 9). Hexane was identified as a bad solvent for the reaction, giving the iodide **7j** in 28% yield and 40% de (entry 10).

The deleterious effect of TMEDA[22] (5 equiv) on the diastereoselectivity of the reaction performed in THF was demonstrated, affording a high 93% yield but a decreased de (65% instead of 74% without additional TMEDA, entry 11). The similar negative effect of LiCl[23] on the course of the reaction was evidenced by carrying out the reaction in the presence of 10 equiv of this salt: though a high yield was obtained, a lower de was recorded (60% instead of 74% without additional salt, entry 12). In order to chelate LiCl (2 equiv), which is generated in situ due to the reaction between $CdCl_2$·TMEDA and Li(TMP) (3 equiv), and check if any effect on the product profile could be seen, we attempted the use of *N*,*N*,*N*′,*N*′-tetraethylethylenediamine (TEEDA), a known lithium chelating ligand.[24] Unfortunately, using additional TEEDA (5 equiv), the product de was lowered to 56%, a result that could be due to a non-selective complexation of the lithium atoms of LiCl (entry 13).

When the reaction was carried out by discarding all TMEDA sources (i.e. using $CdCl_2$ instead of $CdCl_2$·TMEDA to prepare the base), a better 82% de was obtained (entry 14). The de could be

improved to 90% by adding the substrate to the base at room temperature instead of 0 °C (entry 15), but lower (-30 °C) or higher (40 °C) temperatures were less successful (entries 16 and 17).

Table 5. Metalation of chiral ferrocenecarboxylates **6j,k** using lithium-cadmium combinations followed by trapping with I_2.



6j: R,R = Me,Me
6k: R,R = $(CH_2)_5$

7j: R,R = Me,Me
7k: R,R = $(CH_2)_5$

Entry	**6**	Cd source	Solvent, conditions	**7**, Yield (%), de (%)[a]	Yield (%) for **9**, ee (%)[b]
1	**6j**	$CdCl_2$·TMEDA	THF, rt, 2 h	**7j**, 85, 74	89, 71 (S_P)[c]
2			THF, 0 °C, 2 h	**7j**, 87, 75	89, 75 (S_P)[c]
3			THF, -20 °C, 2 h	**7j**, 93, 65	[d]
4	**6j**	$CdCl_2$·TMEDA	THF, rt, 0.5 h	**7j**, 87, 74	[d]
5			THF, rt, 6 h	**7j**, 91, 74	[d]
6	**6j**	$CdCl_2$·TMEDA	Et_2O, rt, 2 h	**7j**, 87, 50	94, 51 (S_P)[c]
7			PhMe, rt, 2 h	**7j**, 81, 66	[d]
8[e]			PhMe, rt, 2 h	**7j**, 74, 64	[d]
9			PhMe, TMEDA (5 equiv), rt, 2 h	**7j**, 91, 54	94, 52 (S_P)[c]
10			HexH, TMEDA (5 equiv), rt, 2 h	**7j**, 28[f], 40	90, 37 (S_P)[c]
11	**6j**	$CdCl_2$·TMEDA	THF, TMEDA (5 equiv), rt, 2 h	**7j**, 93, 65	[d]
12			THF, LiCl (10 equiv), rt, 2 h	**7j**, 93, 60	[d]
13			THF, TEEDA (5 equiv), rt, 2 h	**7j**, 52, 56	[d]
14[g]	**6j**	$CdCl_2$	THF, rt, 2 h	**7j**, 87, 82	[d]
15[h]			THF, rt, 2 h	**7j**, 74, 90	[d]
16[i]			THF, -30 to 5 °C in 2 h	**7j**, 93, 70	[d]
17[j]			THF, 40-50 °C, 2 h	**7j**, 89, 61	[d]
18[k]	**6j**	$CdCl_2$·TMEDA	THF, rt, 2 h	**7j**, 77, 61	93, 57 (S_P)[c]
19	**6k**	$CdCl_2$·TMEDA	THF, rt, 2 h	**7k**, 93, 54	94, 58 (S_P)[c]

[a] Determined from the integration of the ^{1}H NMR spectrum of the crude mixture.
[b] Determined by HPLC analysis on a chiral stationary phase (AS-H column, eluent: 9:1 hexane-isopropanol, 1 mL/min, λ = 252 nm).
[c] The attribution of the configuration was made on the basis of previously reported data.[21]
[d] Reduction not performed.
[e] **6j** was added after removal of LiCl by filtration.
[f] Estimated yield, due to the presence of starting material.
[g] Substrate added at 0 °C.
[h] Substrate added at room temperature.
[i] Substrate added at -30 °C.
[j] Substrate added at 40 °C.
[k] Using the base in situ prepared from $CdCl_2$·TMEDA (1 equiv), Li(TMP) (2 equiv) and BuLi (1 equiv).

In order to check the importance of the composition of the base on the course of the reaction, the use of a reagent in situ prepared from $CdCl_2$·TMEDA (1 equiv), Li(TMP) (2 equiv) and BuLi (1 equiv)[8c] was attempted; upon reaction in THF at room temperature, the deprotonation still took place albeit

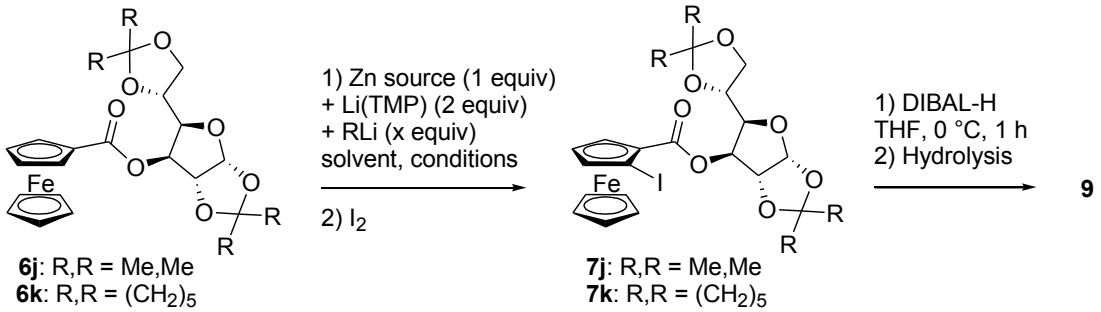
resulting in a lower yield but with a 61% de (against 74% using the all TMP base, entry 18). Additionally, in a bid to improve the diastereoselectivities, the protective group of the diol was modified from a diisopropylidene to a dicyclohexylidene. When the derivative **6k** was employed in the reaction instead of the corresponding derivative **6j**, a 54% de was obtained against 74% when **6j** was the chiral ester (entry 19).

Lithium-zinc combinations were also employed to attempt the diastereoselective deproto-metalation of ferrocene carboxylate **6j** (Table 6). The first reaction was performed using 1 equiv of the all TMP base in THF at room temperature for 2 h. After interception as before, the iodide **7j** was isolated in 86% yield and 54% de (entry 1), a result less interesting than that obtained with the corresponding lithium-cadmium base (Table 5, entry 1). By performing the reaction at -30 °C or -50 °C using the base prepared from $ZnCl_2$·TMEDA (1 equiv) and Li(TMP) (4 equiv), the de was increased by about 10% (entries 2 and 3). In contrast, when the reaction mixture was warmed to room temperature after combining base and substrate at -30 °C, a moderate 53-56% de (similar to that obtained under the conditions described for entry 1) was noted (entries 4-6). By using the base prepared from $ZnCl_2$ instead of $ZnCl_2$·TMEDA, the efficiency of the deproto-metalation was lowered, even when TMEDA (1 equiv) was present in THF at the beginning of the reaction (entry 5) or added later (entry 6). Lower yields and des were noted by using hexane containing 5 equiv of TMEDA[7a] or dimethoxymethane (DMM) as solvent (entries 7 and 8).

The base prepared from $ZnCl_2$·TMEDA (1 equiv) and Li(TMP) (3 equiv) being a 1:1 mixture of $Zn(TMP)_2$ and Li(TMP),[7i] the effect on the diastereoselectivity of adding separately both amides was studied. To this purpose, the addition to a THF solution of the substrate **6f** containing $ZnCl_2$·TMEDA (1 equiv) and Li(TMP) (2 equiv) of a THF solution of Li(TMP) (1 or 2 equiv) was attempted. After 2 h stirring at this temperature and iodolysis, the de was slightly improved to reach 64 or 72%, respectively (entries 9 and 10). A similar diastereoselectivity was obtained by adding Li(TMP) (3 equiv) to a mixture of $ZnCl_2$·TMEDA and **6f** under the same conditions (entry 11).

In the case of the lithium-zinc base, a deleterious effect of TMEDA on the diastereoselectivity was not observed (54% de with and without TMEDA, entry 12). In the case of the mixed lithium-zinc base, replacing one TMP by a butyl group[7e] did not reduce the diastereoselectivity, and a 55% de (entry 13), slightly lower than that noted using the corresponding lithium-cadmium base (Table 5, entry 18), was obtained. The impact of the diol protection was also checked using the all TMP lithium-zinc base; no difference was noticed between the diisopropylidene **6j** and the corresponding dicyclohexylidene **6k** (entry 14).

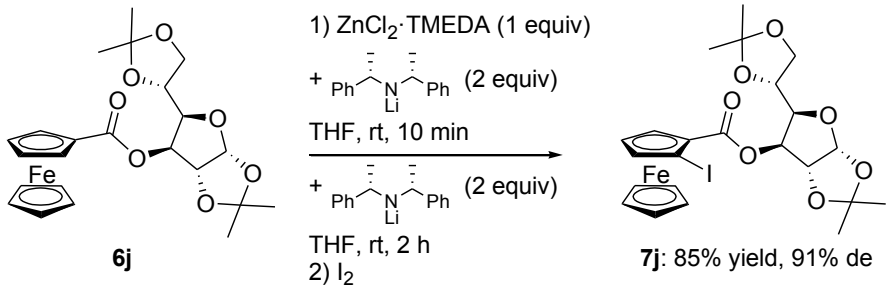
Table 6. Metalation of chiral ferrocenecarboxylates **6j,k** using lithium-zinc combinations followed by trapping with I_2.



Entry	**6**	Zn source	R (x)	Solvent, conditions	**7**, Yield (%), de (%)[a]
1	**6j**	$ZnCl_2$·TMEDA	TMP (1)	THF, rt, 2 h	**7j**, 86, 54 (S_P)[b]
2	**6j**	$ZnCl_2$·TMEDA	TMP (2)	THF, -30 °C, 2 h	**7j**, 82, 66 (S_P)[b]
3[c]		$ZnCl_2$·TMEDA	TMP (2)	THF, -50 °C, 5 h	**7j**, 71, 65 (S_P)[b]
4		$ZnCl_2$·TMEDA	TMP (2)	THF, -30 °C to rt, 2 h	**7j**, 86, 56 (S_P)[b]
5		$ZnCl_2$	TMP (2)	THF, TMEDA (1 equiv), -30 °C to rt, 2 h	**7j**, 30, 56 (S_P)[b]
6[d]		$ZnCl_2$	TMP (2)	THF, TMEDA (1 equiv), -30 °C to rt, 2 h	**7j**, 46, 53 (S_P)[b]
7	**6j**	$ZnCl_2$·TMEDA	TMP (1)	HexH, TMEDA (5 equiv), rt, 2 h	**7j**, 50, 42 (S_P)[b,e]
8		$ZnCl_2$	TMP (2)	DMM, rt, 2 h	**7j**, 32, 51 (S_P)[b]
9[f]	**6j**	$ZnCl_2$·TMEDA	TMP (1)	THF, rt, 2 h	**7j**, 89, 64 (S_P)[b]
10[f]		$ZnCl_2$·TMEDA	TMP (2)	THF, -30 °C to rt, 2 h	**7j**, 87, 72 (S_P)[b]
11		$ZnCl_2$·TMEDA	[g]	THF, -30 °C to rt, 2 h	**7j**, 70, 68 (S_P)[b]
12	**6j**	$ZnCl_2$	TMP (1)	THF, rt, 2 h	**7j**, 68, 54 (S_P)[b]
13[h]	**6j**	$ZnCl_2$·TMEDA	Bu (1)	THF, rt, 2 h	**7j**, 89, 55 (S_P)[b,i]
14	**6k**	$ZnCl_2$·TMEDA	TMP (1)	THF, rt, 2 h	**7k**, 87, 56 (S_P)[b,j]

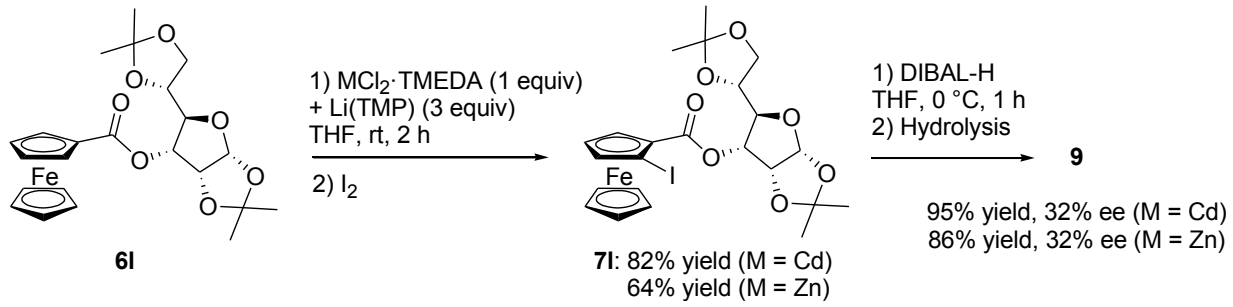
[a] Determined from the integration of the ^{1}H NMR spectrum of the crude mixture.
[b] The attribution of the configuration was made on the basis of previously reported data.[21]
[c] Base transferred to the substrate.
[d] TMEDA slowly added at -30 °C.
[e] Reduction using DIBAL-H provided the alcohol **9** in 94% yield and 42% ee (S_P).
[f] Sequential addition of Li(TMP) (2 equiv) and, 10 min later, RLi (1 or 2 equiv).
[g] Substrate mixed with $ZnCl_2$·TMEDA before addition of Li(TMP) (3 equiv).
[h] Using the base in situ prepared from $ZnCl_2$·TMEDA (1 equiv), Li(TMP) (2 equiv) and BuLi (1 equiv).
[I] Reduction using DIBAL-H provided the alcohol **9** in 93% yield and 60% ee (S_P).
[j] Reduction using DIBAL-H provided the alcohol **9** in 96% yield and 57% ee (S_P).

Double asymmetric induction[25] was attempted using commercial (*R*)- and (*S*)-bis(1-phenylethyl)amine as ligand source instead of 2,2,6,6-tetramethylpiperidine. When **6j** was reacted with a base prepared from $ZnCl_2$·TMEDA (1 equiv) and the (*R*) or (*S*) lithium amide (3 equiv), the iodide **7j** was obtained in 67 and 24% yield, and 79 and 10% de in favor of the (S_P)-diastereoisomer, respectively. In addition, upon treatment by a base prepared from $CdCl_2$ (1 equiv) and the (*R*) lithium amide (3 equiv) under the same reaction conditions, the iodide **7j** was obtained in 97% yield, and 80% de. The sequential addition to a THF solution of the substrate **6j** containing $ZnCl_2$·TMEDA (1 equiv) at room temperature of two THF solutions of (*R*) lithium amide (2 equiv) at 10 min interval was next attempted. Trapping using iodine after 2 h contact led to both good yield and de (Scheme 4).



Scheme 4. Metalation of chiral ferrocenecarboxylate **6j** using a chiral lithium-zinc combination followed by trapping with I_2.

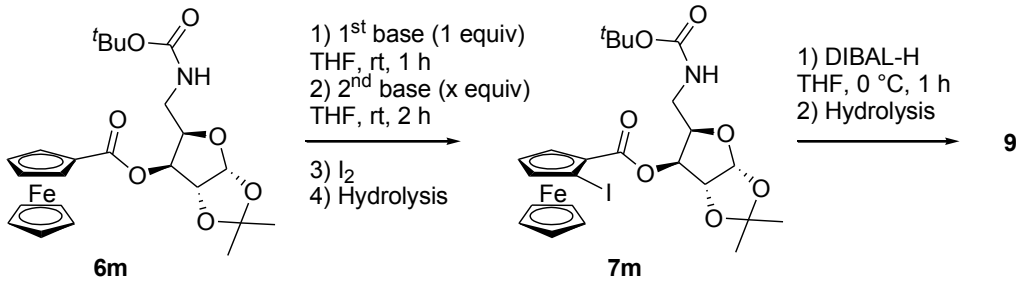
By involving in similar reactions the ester **6l**, which differs from **6j** at the C3 configuration of the sugar substituent, a good conversion to the iodide **7l** was observed (64 and 82% yield using the all TMP lithium-cadmium and lithium-zinc base, respectively) but with a disappointing excess in favor of the S_P diastereoisomer (32% ee in both cases, Scheme 5).



Scheme 5. Metalation of chiral ferrocenecarboxylate **6l** using lithium-cadmium and lithium-zinc bases followed by trapping with I_2.

In order to evaluate chains more coordinating toward metals, we considered the reaction of the ferrocenecarboxylate **6m** (Table 7), generated from 5-(*tert*-butoxycarbonylamino)-5-deoxy-1,2-*O*-isopropylidene-α-D-xylofuranose (**5m**), as the next example. Upon reaction with 1 equiv of the all TMP lithium-cadmium base, **6m** was converted to the corresponding iodide **7m** in 84% yield and in moderate diastereoselectivity (entry 1). In order to improve the diastereoselectivity, pre-treating the substrate with 1 equiv of an organolithium reagent for abstracting the NH proton was considered. The selectivity could be improved but at the cost of the yields (entries 2 and 3). As observed with previous substrates, the lithium-zinc base proved less efficient (entries 4 and 5).

Table 7. Metalation of chiral ferrocenecarboxylates **6m** (or a lithium derivative) using lithium-cadmium and lithium-zinc bases followed by trapping with I_2.



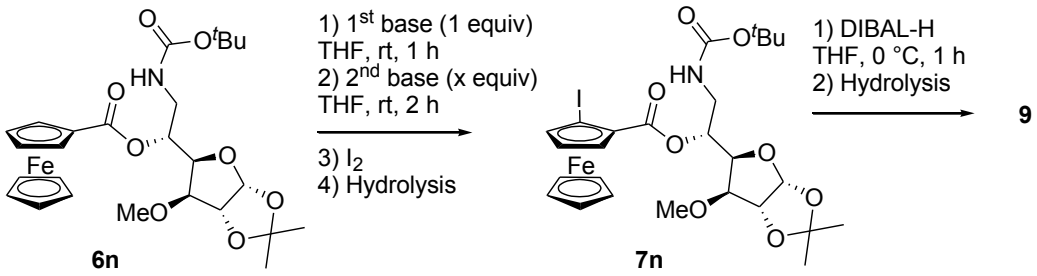
Entry	1st base	2nd base (x)	Yield (%) for **7m**, de (%)[a]	Yield (%) for **9**, ee (%)[b]
1	-	$CdCl_2$·TMEDA (1) + Li(TMP) (3)	84	92, 32 (S_P)[c]
2	BuLi	$CdCl_2$·TMEDA (0.5) + Li(TMP) (1.5)	48	94, 40 (S_P)[c]
3	MeLi	$CdCl_2$·TMEDA (0.75) + Li(TMP) (2.25)	52, 52	96, 56 (S_P)[c]
4	-	$ZnCl_2$·TMEDA (1) + Li(TMP) (3)	40	[d]
5	-	$ZnCl_2$·TMEDA (1.5) + Li(TMP) (4.5)	70	91, 11 (S_P)[c]

[a] When possible, determined from the integration of the ^{1}H NMR spectrum of the crude mixture.
[b] Determined by HPLC analysis on a chiral stationary phase (AS-H column, eluent: 9:1 hexane-isopropanol, 1 mL/min, λ = 252 nm).
[c] The attribution of the configuration was made on the basis of previously reported data.[21]
[d] Reduction not performed.

The ferrocenecarboxylate **6n**, synthesized from 6-(*tert*-butoxycarbonylamino)-6-deoxy-3-*O*-methyl-1,2-*O*-isopropylidene-α-D-glucofuranose (**5n**), showed better results (Table 8). Consecutive treatment with butyllithium (1 equiv) and the all TMP lithium-cadmium base (0.5 equiv) afforded the iodide **7n** in 28% yield and an estimated 60% de, this time in favor of the R_P diastereoisomer (entry 1). Without butyllithium and using 1 equiv of base, the yield was improved, and a similar diastereoselectivity obtained. Under these conditions, both diastereoisomers were separated by column chromatography

over silica gel (entry 2). The main stereoisomer ***R*P-7n** was notably isolated in 34% yield and 98% de and identified unambiguously through its reduction with DIBAL-H to afford ***R*-9**. More importantly, the corresponding but less toxic lithium-zinc base led to similar results (35% yield and 96% de for the stereoisomer ***R*P-7n**, entry 3). When applied to the ester **6n**, the sequential addition of two THF solutions, a first prepared from $ZnCl_2$·TMEDA or $ZnCl_2$ (1 equiv) and Li(TMP) (2 equiv) and, 15 min later, a second of Li(TMP) (2 equiv) afforded ***R*P-7n** in 51 and 57% yield, respectively (entries 4 and 5).

Table 8. Metalation of chiral ferrocenecarboxylates **6n** (or a lithium derivative) using lithium-cadmium and lithium-zinc bases followed by trapping with I_2.



Entry	1st base	2nd base (x)	Yield (%) for **7n**	Yield (%) for **9**, ee (%)[a]
1	BuLi	$CdCl_2$·TMEDA (0.5) + Li(TMP) (1.5)	28[b]	92, 60 (R_P)[c]
2	-	$CdCl_2$·TMEDA (1) + Li(TMP) (3)	34 (***R*P-7n**); 16[d] (***S*P-7n**)[e,f]	90, 98 (R_P)[c]; 91, 93 (S_P)[c]
3	-	$ZnCl_2$·TMEDA (1) + Li(TMP) (3)	35 (***R*P-7n**); 12[d] (***S*P-7n**)[f]	81, 96 (R_P)[c]; 88, 92 (S_P)[c]
4	-	$ZnCl_2$·TMEDA (1) + Li(TMP) (2+2)	51 (***R*P-7n**)[g]	[h]
5	-	$ZnCl_2$ (1) + Li(TMP) (2+2)[i]	57 (***R*P-7n**)[g]	[h]

[a] Determined by HPLC analysis on a chiral stationary phase (AS-H column, eluent: 9:1 hexane-isopropanol, 1 mL/min, λ = 252 nm).
[b] The diiodide **8n** was also isolated in 12% yield.
[c] The attribution of the configuration was made on the basis of previously reported data.[21]
[d] Estimated yield.
[e] The diiodide **8n** was also isolated in 37% yield.
[f] Both diastereoisomers were separated during the purification by column chromatography over silica gel.
[g] Isolation of the other diastereoisomer not performed.
[h] Reduction not performed.
[i] Sequential addition to the substrate of a THF solution prepared from $ZnCl_2$·TMEDA (1 equiv) and Li(TMP) (2 equiv) and, 10 min later, a THF solution of Li(TMP) (2 equiv).

Lithiation experiments on aryl carboxamides showed that the orientation of the functional group has an impact on the efficiency of the metalations at the *ortho* position. In particular, the coplanarity of the oxygen and activated hydrogen within the ring favors the reaction.[26] We first compared the dihedral angle between the upper plane of the ferrocenyl moiety and the ester from the crystal structures of **6c**, **6d**, **6e**, **6i**, **6j**, **6k** and **6l** obtained (Figure 1) with the planar configuration of the main diastereoisomer of **7c**, **7d**, **7e**, **7i**, **7j**, **7k** and **7l** observed (Table 9). Except in the case of **6d** and **6e**, for which des below

10% were recorded, a dihedral angle of about 180° corresponds to major formation of the R_P diastereoisomer and a dihedral angle of about 0° to major formation of the S_P diastereoisomer.

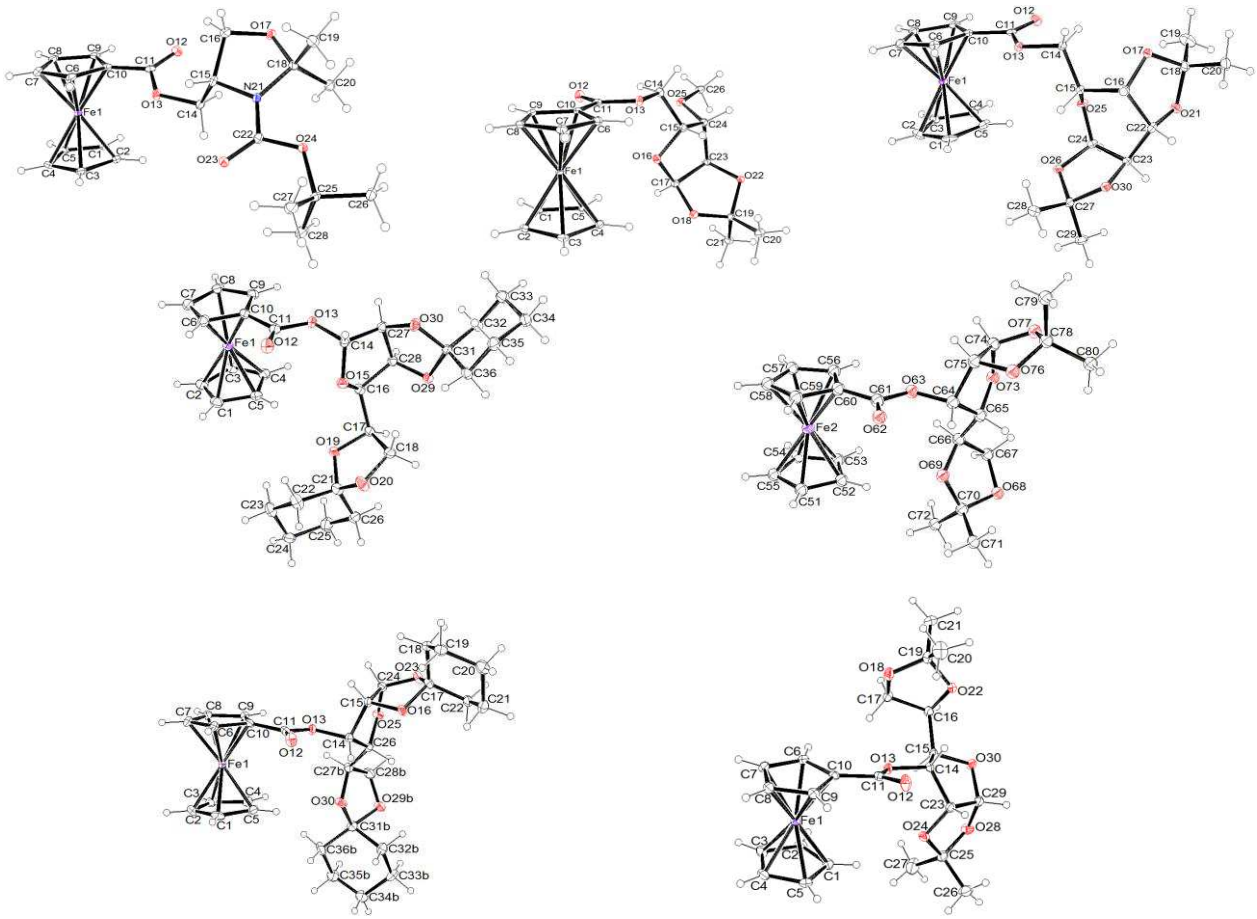


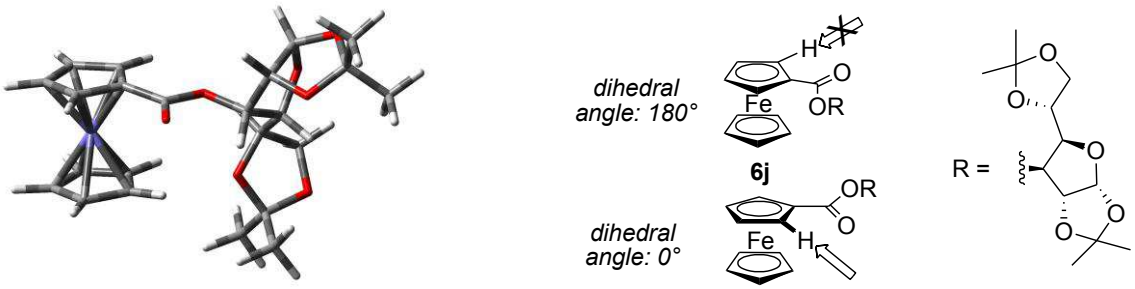
Figure 1. ORTEP diagram (30% probability) of **6c**, **6d**, **6e**, **6i**, **6j**, **6k** and **6l**.

Table 9. Dihedral angle between the upper plane of the ferrocenyl moiety and the ester for **6c**, **6d**, **6e**, **6i**, **6j**, **6k** and **6l**, and expected and observed planar configurations for **7**.

Entry	**6**	Dihedral angle	Expected planar configuration	Observed planar configuration
1	**6c**	about 180°	R_P	R_P (14% de)
2	**6d**	about 180°	R_P	S_P (4% de)
3	**6e**	about 180°	R_P	S_P (8% de)
4	**6i**	about 0°	S_P	S_P (48% de)
5	**6j**	about 0°	S_P	S_P (90% de)
6	**6k**	about 0°	S_P	S_P (56% de)
7	**6l**	about 0°	S_P	S_P (32% de)

We next attempted a rationalization of the diastereoselectivity observed through DFT calculations. While the solid-state structure of **6j** was obtained, we investigated the conformation of **6j** in solution, which should affect the reaction outcome. In order to identify more stable conformers, geometrical

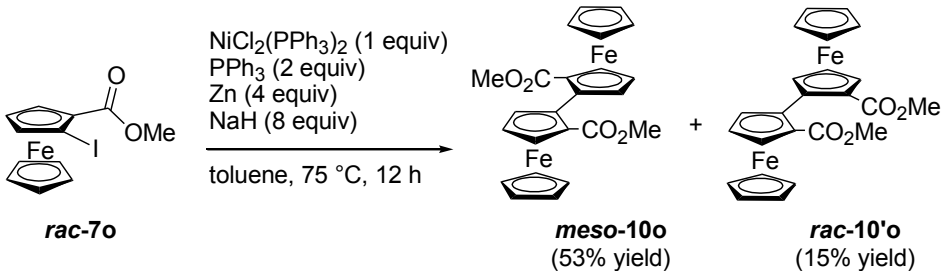
(local stabilization) optimization was performed by changing the dihedral angle between the upper plane of the ferrocenyl moiety and the ester carbonyl group (B3LYP/6-31G(d), structure of the ferrocenyl group fixed). The dihedral angle was fixed with 30° intervals from 0° to 330°. The two most stable structures, with dihedral angles of 0° (to give the major S_P diastereoisomer) and 180° (to give the minor S_P diastereoisomer), were identified and calculated in greater detail (M06/LanL2DZ(Fe)&6-31G(d), SCRF (PCM, solvent = THF)) at around 0° and 180°. The conformation with the dihedral angle of -6.6° proved 4.0 kcal.mol^{-1} lower in energy than that of 180°. The calculation in gas-phase provided almost identical results; the conformation with the dihedral angle of –6.0° proved 4.6 kcal mol^{-1} lower in energy than that of 190°.[14] These calculated results are in accordance with the observed diastereoselectivity in the deproto-metalation of **6j** (Scheme 6).



Scheme 6. Calculated most stable conformer (M06/LanL2DZ(Fe)&6-31G(d)) of **6j** in THF (SCRF calculation) and observed diastereoselectivity in its deproto-metalation.

In order to reach new kinds of ferrocene derivatives, coupling reactions were attempted using the iodoesters **7**. Firstly, it was decided to attempt Ullmann-type coupling reactions on the iodoferrocenecarboxylate ***R*$_P$-7j**, synthesized as described in Scheme 4, and isolated by chromatography over silica gel in about 75% yield. The reagent system comprising $NiCl_2(PPh_3)_2$, triphenylphosphine, zinc and sodium hydride, reported by Lin and Hong in 2001,[27] was attempted for this purpose, but only led to the deiodinated compound **6j**. In contrast, when methyl 2-iodoferrocenecarboxylate ***rac*-7o**, easily prepared by deprotonation-iodination,[7d] was involved in the reaction under the same conditions, the expected self-coupling products were obtained, and separated by chromatography over silica gel

(Scheme 7). The meso derivative ***meso*-10o** and the racemic mixture ***rac*-10'o** were isolated in 53 and 15% yield, respectively, and both were unambiguously identified by X-ray diffraction (Figure 2).



Scheme 7. Homocoupling of racemic methyl 2-iodoferrocenecarboxylate ***rac*-7o**.

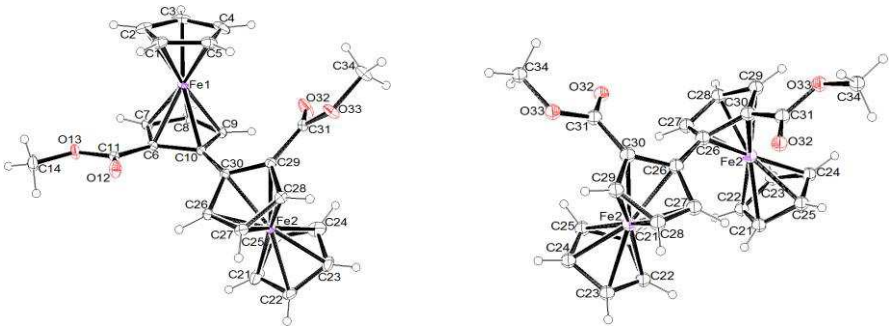
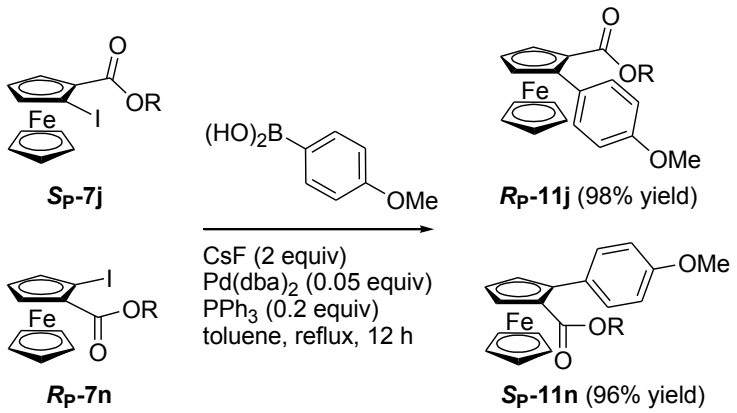


Figure 2. ORTEP diagram (30% probability) of ***meso*-10o** and ***rac*-10'o**.

According to the result obtained from ***rac*-7o**, the reactions between opposite enantiomers (***R*$_P$-7j** and ***S*$_P$-7j**, to afford ***meso*-10o**, 53% yield) appears as more likely than the reactions between same enantiomers (to give ***rac*-10'o**, 15% yield), because of ferrocene-ferrocene hindrance. When the methyl ester is replaced by the sugar-based group (substrate ***R*$_P$-7j**), a meso compound cannot be obtained any more, and the formation of the ***R*$_P$,*R*$_P$** coupled derivative becomes unlikely, probably for steric reasons.

Suzuki-type coupling reactions were finally performed from the 2-iodoferrocenecarboxylates ***S*$_P$-7j** and ***R*$_P$-7n** (Scheme 8). Reaction of 4-methoxyphenylboronic acid with ***rac*-7o** was first carried out as a test reaction in the presence of cesium fluoride in order to avoid the use of basic reagents.[28] The reaction proceeded at the reflux temperature of toluene using catalytic amounts of $Pd(dba)_2$ and triphenylphosphine, affording the expected 4-methoxyphenyl derivative ***rac*-11o** in 97% yield. ***S*$_P$-7j** and ***R*$_P$-7n** were similarly involved in the reaction, affording the coupled products ***R*$_P$-11j** and ***S*$_P$-11n**, respectively.



Scheme 8. Suzuki cross-couplings from 2-iodoferrocenecarboxylates S_P-**7j** and R_P-**7n**.

3. Conclusion

In summary, several chiral esters were screened for their ability to induce diastereoselective deproto-metalation reactions of ferrocenes using mixed lithium-cadmium and lithium-zinc bases. Due to the tolerance of these bimetallic combinations toward reactive functional groups, many substrates were functionalized at room temperature. Among the different groups tested, two proved impressive: the one present in ferrocenecarboxylate **6j**, generated from commercially available inexpensive diacetone-D-glucose (**5j**), allowing the synthesis of the iodo derivative **7j** in either 74% yield and 90% de (S_P diastereoisomer) using the TMEDA-free all TMP lithium-cadmium base or 85% yield and 91% de using a chiral lithium-zinc base (double asymmetric induction), and the one present in ferrocenecarboxylate **6n**, synthesized from 6-(*tert*-butoxycarbonylamino)-6-deoxy-3-*O*-methyl-1,2-*O*-isopropylidene-α-D-glucofuranose (**5n**), leading to the iodo derivative R_P-**7n** in 57% yield.

Through X-ray diffraction data of the ferrocene substrates or/and more accurate calculations of the most stable conformer, we could observe a direct link between the dihedral angle between the upper plane of the ferrocenyl moiety and the ester, and the planar chirality observed in the main diastereoisomer: a dihedral angle of about 180° corresponds to major formation of the R_P diastereoisomer and a dihedral angle of about 0° to major formation of the S_P diastereoisomer.

4. Experimental Section

4.1. General. All reactions were performed in Schlenk tubes under argon atmosphere. THF was distilled over sodium/benzophenone. Liquid chromatography separations were achieved on silica gel Merck-Geduran Si 60 (63-200 μm). Nuclear magnetic resonance spectra were acquired using Bruker AC-300 (300 MHz and 75 MHz for ^{1}H and ^{13}C respectively) or Avance 500 spectrometer (500 MHz and 125 MHz for ^{1}H and ^{13}C respectively). ^{1}H chemical shifts (δ) are given in ppm relative to the solvent residual peak, and ^{13}C chemical shifts relative to the central peak of the solvent signal. High resolution mass spectra measurements were performed at the Centre Régional de Mesures Physiques de l'Ouest (CRMPO) in Rennes. 1,2:3,4-Di-*O*-isopropylidene-α-D-galactopyranose (**5e**), 2,3:5,6-di-*O*-cyclohexylidene-α-D-mannofuranose (**5i**), 1,2:5,6-di-*O*-isopropylidene-α-D-glucofuranose (**5j**), 1,2:5,6-di-*O*-cyclohexylidene-α-D-glucofuranose (**5k**) and 1,2:5,6-di-*O*-isopropylidene-α-D-allofuranose (**5l**) are commercially available. (2*S*,4*S*)-2-Ferrocenyl-4-(methoxymethyl)-1,4-dioxane (**2d**),[16a] (*R*)-2-(4-methoxybenzyloxy)-1-propanol (**5a**),[29] (*R*)-2-(*tert*-butyldiphenylsilyloxy)-1-propanol (**5b**),[30] (*R*)-*N*-(*tert*-butoxycarbonyl)-4-(hydroxymethyl)-2,2-dimethyloxazolidine (**5c**),[31] 1,2-*O*-isopropylidene-3-*O*-methyl-α-D-xylofuranose (**5d**)[32] (1*R*,2*S*)-*N*-(*tert*-butoxycarbonyl)ephedrine (**5f**)[33] and 5-*O*-(*tert*-butyldiphenylsilyl)-1,2-*O*-isopropylidene-α-D-xylofuranose (**5h**)[34] were prepared as previously described.

4.2. 1,2-*O*-Isopropylidene-3,5-*O*-(ferrocenylmethylene)-α-D-xylofuranose (**2c**) was prepared from commercially available 1,2-*O*-isopropylidene-α-D-xylofuranose (**1c**) by transacetalization of the known ferrocene dimethylacetal in chloroform using *p*-toluenesulfonic acid as catalyst.[16a] Purification by flash chromatography on silica gel (eluent: 100:0 to 92:8 heptane-EtOAc) afforded a pale yellow powder (yield: 60% for 2 steps): mp 163-164 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.34 (s, 3H), 1.52 (s, 3H), 4.05-4.21 (m, 9H), 4.30-4.43 (m, 4H), 4.62 (d, 1H, J = 3.7 Hz), 5.29 (s, 1H), 6.05 (d, 1H, J = 3.7 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 26.3, 26.8, 66.7, 67.0, 67.1, 68.5, 68.6, 69.4 (5C), 72.4, 78.8, 84.0, 85.4, 98.3, 105.8, 111.8; $[\alpha]_D$ = -5.5 ($CHCl_3$, c = 0.2, 20 °C). Anal. Calcd for $C_9H_{22}FeO_5$ (386.22): C, 59.09;

H, 5.74. Found: C, 58.76; H, 5.62. The structure was identified unequivocally by X-ray structure analysis (CCDC 970485) from crystals obtained by slowly evaporating a 92:8 heptane-EtOAc solution.

4.3. (2*S*,4*R*)-*tert*-Butyl 4-hydroxy-2-(*tert*-butyldiphenylsilyloxymethyl)-1-pyrrolidinecarboxylate (**5g**) was prepared following a described procedure,[34] and was isolated as a white solid: mp 148 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.03 (s, 9H), 1.32 and 1.47 (s, 9H), 1.94-2.14 (m, 1H), 2.29-2.37 (m, 1H), 3.42-3.77 and 3.97-4.10 (m, 5H), 4.50-4.57 (m, 1H), 7.34-7.42 (m, 6H), 7.60-7.64 (m, 4H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 19.1, 26.6, 26.7 (several C), 28.3, 28.4, 36.6, 37.2, 55.0, 55.1, 55.4, 55.5, 57.0, 57.1, 57.2, 63.7, 63.8, 64.8, 69.4, 70.1, 79.2, 79.3, 79.4, 127.6, 129.5, 133.2-133.4 (4 signals), 135.4 (2 signals), 154.6-154.7 (4 signals); $[\alpha]_D$ = -32 ($CHCl_3$, *c* = 5.0, 20 °C); HRMS: calcd for $C_{26}H_{37}NNaO_4Si$ $[(M+Na)^{+\bullet}]$ 478.2384, found 478.2385.

4.4. 5-(*tert*-Butoxycarbonylamino)-5-deoxy-1,2-*O*-isopropylidene-α-D-xylofuranose (**5m**) and **6-(*tert*-Butoxycarbonylamino)-6-deoxy-3-*O*-methyl-1,2-*O*-isopropylidene-α-D-glucofuranose**[15] (**5n**) were prepared by adapting a described procedure.[35] Their analyses were as described previously.[15]

4.5. General procedure for the reaction of ferrocenecarboxylic acid with chiral alcohols. A solution of ferrocenecarboxylic acid (0.93 g, 4.0 mmol), DCC (0.91 g, 4.4 mmol), the required chiral alcohol (4.0 mmol) and DMAP (0.48 g, 4.4 mmol) in CH_2Cl_2 (40 mL) was heated under reflux for 16 h. *N*,*N*′-dicyclohexylurea was filtered off, and the filtrate was washed with water (3 x 40 mL). After drying over anhydrous Na_2SO_4, the solvent was evaporated under reduced pressure, and the ester was isolated by purification by flash chromatography on silica gel.

4.5.1. (*R*)-2-(4-Methoxybenzyloxy)-1-propyl ferrocenecarboxylate (**6a**) was prepared from **5a** (0.78 g) and was isolated (eluent: 93:7 heptane-EtOAc) as a red oil (yield: 45%): ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.29 (d, 3H, *J* = 6.4 Hz), 3.80 (s, 3H), 3.81-3.87 (m, 1H), 4.18 and 4.31 (AB-part of an ABX system, 2H, J_{AB} = 11.5 Hz, J_{AX} = 6.0 Hz, J_{BX} = 4.2 Hz), 4.20 (s, 3H), 4.40 (t, 2H, *J* = 2.0 Hz), 4.58 and 4.62 (AB, 2H, J_{AB} = 11.5 Hz), 4.81-4.84 (m, 2H), 6.88 (d, 2H, *J* = 8.7 Hz), 7.32 (d, 2H, *J* = 8.7 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 17.4, 55.4, 67.1, 69.9 (5C), 70.3 (2C), 70.9, 71.1, 71.4 (2C), 72.6, 113.9

(2C), 129.4 (2C), 130.7, 159.2, 171.7; $[\alpha]_D$ = +0.83 (CH_2Cl_2, *c* = 1.9, 20 °C). Anal. Calcd for $C_{22}H_{24}FeO_4$ (408.27): C, 64.72; H, 5.93. Found: C, 64.45; H, 5.99.

4.5.2. (*R*)-2-(*tert*-Butyldiphenylsilyloxy)-1-propyl ferrocenecarboxylate (**6b**) was prepared from **5b** (1.3 g) and was isolated (eluent: 93:7 heptane-EtOAc) as an orange oil (yield: 53%): ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.09 (s, 9H), 1.17 (d, 3H, *J* = 6.0 Hz), 4.12 (m, 3H), 4.16 (s, 5H), 4.37 (t, 2H, *J* = 1.9 Hz), 4.8 (br d, 2H, *J* = 9.0 Hz), 7.35-7.43 (m, 6H), 7.72 (m, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 19.4, 20.7, 27.1 (3C), 67.8, 69.3, 69.9 (5C), 70.3, 70.4, 70.7, 71.4 (2C), 127.7 (2C), 127.8 (2C), 129.8, 129.9, 134.1, 134.4, 135.9 (2C), 136.0 (2C), 171.7; $[\alpha]_D$ = -5.7 (CH_2Cl_2, *c* = 0.35, 20 °C). Anal. Calcd for $C_{30}H_{34}FeO_3Si$ (526.52): C, 68.43; H, 6.51. Found: C, 68.77; H, 6.79.

4.5.3. (*S*)-[*N*-(*tert*-Butoxycarbonyl)-2,2-dimethyl-4-oxazolidyl]methyl ferrocenecarboxylate (**6c**) was prepared from **5c** (0.93 g) and was isolated (eluent: 88:12 heptane-EtOAc) as a red powder (yield: 76%): mp 70 °C; ^{1}H NMR (500 MHz, 340 K, C_6D_6) δ 1.44 (s, 9H), 1.51 (s, 3H), 1.69 (s, 3H), 3.74 (dd, 1H, *J* = 6.5, 8.8 Hz), 3.89 (d, 1H, *J* = 8.8 Hz), 4.00 (m, 1H), 4.02 (s, 5H), 4.09 (s, 2H), 4.20 (br m, 1H), 4.56 (dd, 1H, *J* = 3.2, 10.4 Hz), 4.81 (d, 2H, *J* = 6.7 Hz); ^{13}C NMR (125 MHz, 340 K, C_6D_6) δ 23.5, 27.3, 28.6 (3C), 56.7, 63.6, 65.7, 70.1 (5C), 70.7, 70.8, 71.4 (2C), 72.2, 80.0, 94.4, 152.1, 170.7; $[\alpha]_D$ = -16 (CH_2Cl_2, *c* = 1.0, 20 °C). Anal. Calcd for $C_{22}H_{29}FeNO_5$ (443.31): C, 59.60; H, 6.59; N, 3.16. Found: C, 59.30; H, 6.54; N, 3.11. The structure was identified unequivocally by X-ray structure analysis (CCDC 970486) from crystals obtained by slowly evaporating a 2:8 EtOAc-heptane solution.

4.5.4. 6-*O*-(Ferrocenecarbonyl)-1,2-*O*-isopropylidene-3-*O*-methyl-α-D-xylofuranose (**6d**) was prepared as described previously.[15] Its structure was identified unequivocally by X-ray structure analysis (CCDC 798861) from crystals obtained by slowly evaporating a 2:8 CH_2Cl_2-pentane solution.

4.5.5. 6-*O*-(Ferrocenecarbonyl)-1,2:3,4-di-*O*-isopropylidene-α-D-galactopyranose (**6e**) was prepared as described previously.[15] Its structure was identified unequivocally by X-ray structure analysis (CCDC 798860) from crystals obtained by slowly evaporating a CH_2Cl_2 solution.

4.5.6. (1*R*,2*S*)-2-[*N*-(*tert*-Butoxycarbonyl)-*N*-methylamino]-1-phenylpropyl ferrocenecarboxylate (**6f**) was prepared from **5f** (1.1 g) and was isolated (eluent: 92:8 heptane-EtOAc) as a red oil (yield: 38%): ^{1}H NMR (500 MHz, 340 K, C_6D_6) δ 1.22 (d, 3H, *J* = 6.9 Hz), 1.36 (s, 9H), 2.59 (br s, 3H), 3.89 (s, 5H), 4.08 (s, 2H), 4.74 (br s, 1H), 4.77 (br s, 1H), 4.83 (br s, 1H), 6.22 (d, 1H, *J* = 8.1 Hz), 7.07 (t, 1H, *J* = 7.3 Hz), 7.16 (m, 2H), 7.52 (d, 2H, *J* = 7.4 Hz); ^{13}C NMR (125 MHz, 340 K, C_6D_6) δ 14.4, 28.5 (3C), 30.1, 55.2, 70.0 (5C), 70.5, 70.7, 71.3, 71.4, 72.4, 77.4, 79.2, 127.8-128.4 (5C), 139.8, 155.3, 169.9; $[\alpha]_D$ = +47.6 (CH_2Cl_2, *c* = 2.5, 20 °C). Anal. Calcd for $C_{26}H_{31}FeNO_4$ (477.37): C, 65.42; H, 6.55; N, 2.93. Found: C, 65.34; H, 6.63; N, 3.03.

4.5.7. (2*S*,4*R*)-1-*tert*-Butoxycarbonyl-2-(*tert*-butyldiphenylsilyloxymethyl)-4-pyrrolidyl ferrocenecarboxylate (**6g)** was prepared from **5g** (1.8 g) using DCC (1.2 g, 6.0 mmol) and DMAP (0.65 g, 6.0 mmol) in CH_2Cl_2 (20 mL), and was isolated (eluent: 93:7 heptane-EtOAc) as an orange gum (yield: 83%): ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.06 (s, 9H), 1.36 and 1.48 (s, 9H), 2.17-2.33 (m, 1H), 2.44-2.56 (m, 1H), 3.63-3.90 (m, 4H), 4.05-4.23 (m, 1H), 4.20 (s, 5H), 4.40 (br s, 2H), 4.77-4.80 (m, 2H), 5.47-5.51 (m, 1H), 7.36-7.43 (m, 6H), 7.63-7.68 (m, 4H); ^{13}C NMR (75 MHz, $CDCl_3$) mixture of conformers δ 19.1, 19.2, 19.2, 26.8, 28.4, 28.5, 33.7, 35.0, 52.5, 53.3, 57.3, 57.3, 57.3, 63.8, 64.9, 69.7 (several C), 69.9, 70.1, 70.2, 70.7, 70.9, 71.3, 71.3, 71.4, 72.3, 72.3, 72.9, 76.5, 79.6, 127.6, 127.7, 127.7, 129.6, 129.6, 129.7, 133.2, 135.5, 154.2, 154.3, 171.2, 171.4; $[\alpha]_D$ = -36.5 ($CHCl_3$, *c* = 0.41, 20 °C); HRMS: calcd for $C_{37}H_{45}{}^{56}FeNNaO_5Si$ $[(M+Na)^{+\bullet}]$ 690.2309, found 690.2308.

4.5.8. 3-*O*-(Ferrocenecarbonyl)-5-*O*-(*tert*-butyldiphenylsilyl)-1,2-*O*-isopropylidene-α-D-xylofuranose (**6h**) and **1-*O*-(ferrocenecarbonyl)-2,3:5,6-di-*O*-cyclohexylidene-α-D-mannofuranose** (**6i**) were prepared as described previously.[15] The structure of **6i** was identified unequivocally by X-ray structure analysis (CCDC 798862) from crystals obtained by slowly evaporating a 7:3 hexane-CH_2Cl_2 solution.

4.5.9. 3-*O*-(Ferrocenecarbonyl)-1,2:5,6-di-*O*-isopropylidene-α-D-glucofuranose (**6j**) was prepared as described previously.[15] Its structure was identified unequivocally by X-ray structure analysis (CCDC 798863) from crystals obtained by slowly evaporating a 1:1 pentane-CH_2Cl_2 solution.

4.5.10. 3-*O*-(Ferrocenecarbonyl)-1,2:5,6-di-*O*-cyclohexylidene-α-D-glucofuranose[15] (**6k**) was prepared as described previously.[15] Its structure was identified unequivocally by X-ray structure analysis (CCDC 970487) from crystals obtained by slowly evaporating a 7:3 hexane-CH_2Cl_2 solution.

4.5.11. 3-*O*-(Ferrocenecarbonyl)-1,2:5,6-di-*O*-isopropylidene-α-D-allofuranose (**6l**) was prepared as described previously.[15] Its structure was identified unequivocally by X-ray structure analysis (CCDC 798864) from crystals obtained by slowly evaporating a 7:3 hexane-CH_2Cl_2 solution.

4.5.12. 5-(*tert*-Butoxycarbonylamino)-5-deoxy-3-*O*-(ferrocenecarbonyl)-1,2-*O*-isopropylidene-α-D-xylofuranose (**6m**) and **6-(*tert*-butoxycarbonylamino)-6-deoxy-5-*O*-(ferrocenecarbonyl)-1,2-*O*-isopropylidene-3-*O*-methyl-α-D-glucofuranose** (**6n**) were prepared as described previously.[15,14]

4.6. (2*S*,4*S*)-2-(2-Iodoferrocenyl)-4-(methoxymethyl)-1,4-dioxane (diastereoisomeric mixture) (**3d**). To a stirred cooled (0 °C) solution of 2,2,6,6-tetramethylpiperidine (0.68 mL, 4.0 mmol) in THF (5 mL) were successively added BuLi (1.6 M hexanes solution, 4.0 mmol) and, 5 min later, $ZnCl_2$·TMEDA[7e] (0.51 g, 2.0 mmol). The mixture was stirred for 10 min at 0 °C before introduction of **2d** (0.63 g, 2.0 mmol). After 10 min at room temperature, a cooled (-30 °C) solution prepared in THF (5 mL) from 2,2,6,6-tetramethylpiperidine (0.68 mL, 4.0 mmol) and BuLi (1.6 M hexanes solution, 4.0 mmol) was added, and the resulting mixture was stirred for 2 h at -30 °C before a solution of I_2 (2.0 g, 8.0 mmol) in THF (5 mL) was added. The mixture was stirred overnight before addition of an aq saturated solution of $Na_2S_2O_3$ (10 mL) and extraction with EtOAc (3 x 20 mL). After drying over anhydrous Na_2SO_4, the solvent was evaporated under reduced pressure, and the iodide **3d** was isolated by purification by flash chromatography on silica gel (eluent: 9:1 heptane-EtOAc) in an estimated 45% yield. A 79% de was determined by NMR. The minor isomer was identified as (2*S*,4*S*,R_P)-2-(2-iodoferrocenyl)-4-(methoxymethyl)-1,4-dioxane (***R*$_P$-3d**) by comparison with reported ^{13}C NMR data in

C_6D_6:[16r] ^{13}C NMR (75 MHz, C_6D_6) δ 28.0 (CH_2), 42.4 (C), 59.1 (CH_3), 66.8 (CH_2), 67.0 (CH), 69.0 (CH), 72.3 (5CH), 75.0 (CH), 75.9 (CH_2), 76.4 (CH), 87.3 (C), 100.9 (CH); ^{13}C NMR (75 MHz, $CDCl_3$) δ 27.9 (CH_2), 41.7 (C), 59.6 (CH_3), 66.3 (CH), 67.0 (CH_2), 68.9 (CH), 72.0 (5CH), 74.8 (CH), 75.7 (CH_2), 76.4 (CH), 86.4 (C), 100.7 (CH). The major isomer proved to be (2*S*,4*S*,*S*$_P$)-2-(2-iodoferrocenyl)-4-(methoxymethyl)-1,4-dioxane (***S*$_P$-3d**): ^{13}C NMR (75 MHz, C_6D_6) δ 28.5 (CH_2), 42.1 (C), 59.1 (CH_3), 66.9 (CH), 66.9 (CH_2), 68.9 (CH), 72.2 (5CH), 75.1 (CH), 75.6 (CH_2), 76.5 (CH), 87.5 (C), 101.0 (CH); ^{13}C NMR (75 MHz, $CDCl_3$) δ 28.1 (CH_2), 41.6 (C), 59.4 (CH_3), 66.3 (CH), 67.1 (CH_2), 68.8 (CH), 71.9 (5CH), 75.0 (CH), 75.4 (CH_2), 76.3 (CH), 86.1 (C), 101.0 (CH).

4.7. (a) General procedure for the deprotonation using the lithium-cadmium base prepared from $CdCl_2$·TMEDA (1 equiv) and Li(TMP) (3 equiv) in THF followed by trapping using I_2. To a stirred cooled (0 °C) solution of 2,2,6,6-tetramethylpiperidine (1.1 mL, 6.0 mmol) in THF (5 mL) were successively added BuLi (1.6 M hexanes solution, 6.0 mmol) and, 5 min later, $CdCl_2$·TMEDA[36] (0.60 g, 2.0 mmol). The mixture was stirred for 10 min at 0 °C before introduction of the required substrate (2.0 mmol). After 2 h at room temperature, a solution of I_2 (1.5 g, 6.0 mmol) in THF (5 mL) was added. The mixture was stirred overnight before addition of an aq saturated solution of $Na_2S_2O_3$ (10 mL) and extraction with EtOAc (3 x 20 mL). After drying over anhydrous Na_2SO_4, the solvent was evaporated under reduced pressure, and the iodide was isolated by purification by flash chromatography on silica gel. **(b) General procedure for the conversion of 2-iodoferrocenecarboxylates 7 to 2-iodoferrocenemethanol (9).**[21] The required diastereoisomeric mixture of iodoferrocenecarboxylates **7** (0.30 mmol) was dissolved in THF (3 mL), and a 1.0 M DIBAL-H solution in heptane (1.2 mL, 1.2 mmol) was added dropwise at 0 °C. The mixture was stirred at this temperature for 1 h before quenching by addition of MeOH (0.5 mL), dilution with Et_2O (10 mL), and addition of an aqueous saturated solution of sodium and potassium tartrate (10 mL) at 0 °C. After stirring for 30 min at room temperature, extraction with Et_2O and drying over anhydrous Na_2SO_4, the solvent was evaporated under reduced pressure, and 2-iodoferrocenemethanol (**9**) was isolated as orange crystals by purification

by flash chromatography on silica gel (eluent: 88:12 heptane-EtOAc). HPLC analysis on a chiral stationary phase (AS-H column, eluent: 9:1 hexane-isopropanol, 1 mL/min, λ = 252 nm) gave two well separated peaks for the two enantiomers of 2-iodoferrocenemethanol (***R***$_P$**-9**, 12.5 min, and ***S***$_P$**-9**, 22.2 min).

4.7.1. (2*S*,4*S*)-2-(2,5-Diiodoferrocenyl)-4-(methoxymethyl)-1,4-dioxane (**4d**) was prepared from **2d** (0.63 g) using **4.7. (a)** and was isolated (eluent: 85:15 heptane-EtOAc) as an orange oil (yield: 79%): ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.50 (ddd, 1H, *J* = 13.0, 3.8 and 2.3 Hz), 1.86 (ddd, 1H, *J* = 16.6, 12.5 and 5.0 Hz), 3.45 (s, 3H), 3.48 (dd, 1H, *J* = 10.2 and 4.8 Hz), 3.63 (dd, 1H, *J* = 10.2 and 6.4 Hz), 3.94 (td, 1H, *J* = 12.1 and 2.5 Hz), 4.08 (dddd, 1H, *J* = 11.2, 6.7, 4.6 and 2.4 Hz), 4.22 (s, 5H), 4.29 (ddd, 1H, *J* = 11.3, 4.9 and 1.2 Hz), 4.49 (d, 1H, *J* = 2.4 Hz), 4.52 (d, 1H, *J* = 2.4 Hz), 5.45 (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 28.0 (CH_2), 39.0 (C), 40.7 (C), 59.6 (CH_3), 67.2 (CH_2), 75.1 (5CH), 75.8 (CH_2), 76.4 (CH), 76.6 (CH), 77.1 (CH), 85.1 (C), 100.8 (CH). Anal. Calcd for $C_{16}H_{18}FeI_2O_3$ (567.97): C, 33.83; H, 3.19. Found: C, 33.70; H, 3.41.

4.7.2. (*R*)-2-(4-Methoxybenzyloxy)-1-propyl 2,5-diiodoferrocenecarboxylate (**8a**) was prepared from **6a** (0.82 g) using **4.7. (a)** and was isolated (eluent: 94:6 heptane-EtOAc) as a red oil (yield: 29%): ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.38 (d, 3H, *J* = 6.3 Hz), 3.78 (s, 3H), 3.96 (hex, 1H, *J* = 5.6 Hz), 4.24 (s, 5H), 4.32 and 4.41 (AB-part of an ABX system, 2H, J_{AB} = 11.4 Hz, J_{AX} = 5.5 Hz, J_{BX} = 4.6 Hz), 4.58 and 4.64 (AB, 2H, J_{AB} = 11.4 Hz), 4.76 (s, 2H), 6.86 (d, 2H, *J* = 8.6 Hz), 7.33 (d, 2H, *J* = 8.6 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 17.9, 39.0 (2C), 55.4, 67.5, 70.8, 72.6, 73.3, 75.9 (5C), 80.6 (2C), 113.9 (2C), 129.5 (2C), 130.6, 159.2, 168.8; $[\alpha]_D$ = -9.7 (CH_2Cl_2, *c* = 1.5, 20 °C). Anal. Calcd for $C_{22}H_{22}FeI_2O_4$ (660.06): C, 40.03; H, 3.36. Found: C, 40.07; H, 3.42.

4.7.3. (*R*)-2-(*tert*-Butyldiphenylsilyloxy)-1-propyl 2,5-diiodoferrocenecarboxylate (**8b**) was prepared from **6b** (1.1 g) using **4.7. (a)** and was isolated (eluent: 96:4 pentane-Et_2O) as a red oil (yield: 68%). The analyses were as described previously.[7d]

4.7.4. (*S*)-[*N*-(*tert*-Butoxycarbonyl)-2,2-dimethyl-4-oxazolidyl]methyl 2-iodoferrocenecarboxylate (diastereoisomeric mixture) (**7c**) was prepared from **6c** (0.89 g) using **4.7. (a)** but could not be separated from the starting material (estimated yield: 18%), and the mixture was treated with DIBAL-H according to **4.7. (b)** to afford 2-iodoferrocenemethanol (**9**) in 98% yield and 14% ee (R_P).

4.7.5. 3-*O*-(2-Iodoferrocenecarbonyl)-1,2:5,6-di-*O*-cyclohexylidene-α-D-glucofuranose (diastereoisomeric mixture) (**7k**) was prepared from **6k** (1.1 g) using **4.7. (a)** and was isolated (eluent: 95:5 heptane-EtOAc) as an orange solid (93% yield). A 54% de was determined by NMR. The analyses were as described previously.[15] Treatment with DIBAL-H according to **4.7. (b)** afforded 2-iodoferrocenemethanol (**9**) in 94% yield and 58% ee (S_P).

4.7.6. 3-*O*-(2-Iodoferrocenecarbonyl)-1,2:5,6-di-*O*-isopropylidene-α-D-allofuranose (diastereoisomeric mixture)[15,14] (**7l**) was prepared from **6l** (0.94 g) using **4.7. (a)** but could not be separated from the starting material (estimated yield: 82%). It was identified by HRMS: calcd for $C_{23}H_{27}{}^{56}FeINaO_7$ $[(M+Na)^{+\bullet}]$ 621.0043, found 621.0043. The mixture was treated with DIBAL-H according to **4.7. (b)** to afford 2-iodoferrocenemethanol (**9**) in 95% yield and 32% ee (S_P).

4.7.7. 6-(*tert*-Butoxycarbonylamino)-6-deoxy-5-*O*-(2,5-diiodoferrocenecarbonyl)-1,2-*O*-isopropylidene-3-*O*-methyl-α-D-glucofuranose (8n) was prepared from **6n** (1.1 g) using **4.7. (a)** and was isolated (eluent: 3:7 heptane-EtOAc) as a yellow liquid (yield: 37%): ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.32 (s, 3H), 1.42 (s, 9H), 1.50 (s, 3H), 3.41 (s, 3H), 3.53-3.62 (m, 1H), 3.79-3.87 (m, 1H), 3.93 (d, 1H, J = 3.2 Hz), 4.27 (s, 5H), 4.43 (dd, 1H, J = 6.7, 3.1 Hz), 4.58 (d, 1H, J = 5.2 Hz), 4.78 (s, 2H), 5.11 (t, 1H, J = 5.2 Hz), 5.43-5.49 (m, 1H), 5.93 (d, 1H, J = 3.7 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 26.4, 27.1, 28.6 (3C), 41.9, 58.2, 70.6 (2C), 76.1 (5C), 79.4, 79.9, 80.7, 80.8, 80.9, 81.4, 83.9, 105.3 (2C), 112.0, 155.9, 168.0; $[\alpha]_D$ = -10 (CH_2Cl_2, c = 1.1, 20 °C). Anal. Calcd for $C_{26}H_{33}FeI_2NO_8$ (797.20): C, 39.17; H, 4.17; N, 1.76. Found: C, 39.52; H, 4.45; N, 1.67.

4.8. General procedure for the deprotonation using the lithium-cadmium base prepared from $CdCl_2$·TMEDA (0.5 equiv) and Li(TMP) (1.5 equiv) in THF followed by trapping using I_2. To a stirred cooled (0 °C) solution of 2,2,6,6-tetramethylpiperidine (1.1 mL, 6.0 mmol) in THF (5 mL) were successively added BuLi (1.6 M hexanes solution, 6.0 mmol) and, 5 min later, $CdCl_2$·TMEDA[36] (0.60 g, 2.0 mmol). The mixture was stirred for 10 min at 0 °C before introduction of the required substrate (4.0 mmol). After 2 h at room temperature, a solution of I_2 (1.5 g, 6.0 mmol) in THF (5 mL) was added. The mixture was stirred overnight before addition of an aq saturated solution of $Na_2S_2O_3$ (10 mL) and extraction with EtOAc (3 x 20 mL). After drying over anhydrous Na_2SO_4, the solvent was evaporated under reduced pressure, and the iodide was isolated by purification by flash chromatography on silica gel.

4.8.1. (*R*)-2-(4-Methoxybenzyloxy)-1-propyl 2-iodoferrocenecarboxylate (diastereoisomeric mixture) (**7a**) was prepared from **6a** (1.6 g) and was isolated (eluent: 94:6 heptane-EtOAc) as a red oil (yield: 76%): ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.32 (2d, 3H, *J* = 6.4 Hz), 3.79 and 3.80 (2s, 3H), 3.83-3.94 (m, 1H), 4.21-4.22 (2s, 5H), 4.17-4.46 (m, 3H), 4.56-4.65 (m, 2H), 4.69-4.71 (m, 1H), 4.85-4.88 (m, 1H), 6.90-6.95 (m, 2H), 7.29-7.34 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 17.5 (2 peaks), 39.8, 55.4, 67.0, 67.3, 70.4 (2 peaks), 70.8, 70.9, 72.4, 72.6, 72.7, 72.9 (5C), 76.0, 79.9, 113.9 (2C), 129.4 (2 peaks, 2C), 130.7, 159.3, 170.2, 170.3. Anal. Calcd for $C_{22}H_{23}FeIO_4$ (534.17): C, 49.47; H, 4.34. Found: C, 49.20; H, 4.21. Treatment with DIBAL-H according to **4.7. (b)** afforded 2-iodoferrocenemethanol (**9**) in 94% yield and 7% ee (S_P).

4.8.2. (*R*)-2-(*tert*-Butyldiphenylsilyloxy)-1-propyl 2-iodoferrocenecarboxylate (diastereoisomeric mixture) (**7b**) was prepared from **6b** (2.1 g) and was isolated (eluent: 94:6 heptane-Et_2O) as a red powder (yield: 54%): mp 126 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.08 and 1.09 (2s, 9H), 1.21 and 1.25 (2d, 3H, *J* = 5.9 Hz), 4.10-4.22 (m, 8H), 4.41 (q, 1H, *J* = 2.7 Hz), 4.67-4.69 (m, 1H), 4.77-4.78 (m, 1H), 7.33-7.44 (m, 6H), 7.68-7.73 (m, 4H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 19.4, 20.8, 27.1 (3C), 39.8, 67.7, 67.8, 69.4 (2 peaks), 70.3, 72.3 (2 peaks), 72.9 (2 peaks, 5C), 79.9, 127.8 (2 peaks, 4C), 129.8

(2C), 134.0 (2 peaks), 134.3 (2 peaks), 136.0 (2 peaks, 4C), 170.2. Anal. Calcd for $C_{30}H_{33}FeIO_3Si$ (652.42): C, 55.23; H, 5.10. Found: C, 55.08; H, 5.34. Treatment with DIBAL-H according to **4.7. (b)** afforded 2-iodoferrocenemethanol (**9**) in 98% yield and 1% ee (S_P).

4.8.3. 5-*O*-(2-Iodoferrocenecarbonyl)-1,2-*O*-isopropylidene-3-*O*-methyl-α-D-xylofuranose (diastereoisomeric mixture) (**7d**) was prepared from **6d** (1.7 g) and was isolated (eluent: 88:12 heptane-EtOAc) as a red oil (yield: 92%). The analyses were as described previously.[15] Treatment with DIBAL-H according to **4.7. (b)** afforded 2-iodoferrocenemethanol (**9**) in 93% yield and 4% ee (S_P). **5-*O*-(2,5-Diiodoferrocenecarbonyl)-1,2-*O*-isopropylidene-3-*O*-methyl-α-D-xylofuranose (8d)** was isolated similarly in 3% yield as a red liquid, and was identified by NMR: ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.34 (s, 3H), 1.52 (s, 3H), 3.46 (s, 3H), 3.95 (d, 1H, J = 2.7 Hz), 4.26 (s, 5H), 4.52-4.65 (m, 4H), 4.77 (s, 2H), 5.97 (d, 1H, J = 3.8 Hz); $[\alpha]_D$ = -19 (CH_2Cl_2, c = 0.11, 20 °C).

4.8.4. 6-*O*-(2-Iodoferrocenecarbonyl)-1,2:3,4-di-*O*-isopropylidene-α-D-galactopyranose (diastereoisomeric mixture) (7e) was prepared from **6e** (1.9 g) and was isolated (eluent: 75:25 heptane-Et_2O) as an orange powder (yield: 82%). The analyses were as described previously.[15] Treatment with DIBAL-H according to **4.7. (b)** afforded 2-iodoferrocenemethanol (**9**) in 95% yield and 8% ee (S_P). **6-*O*-(2,5-Diiodoferrocenecarbonyl)-1,2:3,4-di-*O*-isopropylidene-α-D-galactopyranose (8e)** was isolated similarly in 4% yield as a red liquid, and was identified by NMR: ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.34 (s, 3H), 1.36 (s, 3H), 1.49 (s, 3H), 1.60 (s, 3H), 4.29-4.33 (m, 6H), 4.37 (dd, 1H, J = 5.0, 2.5 Hz), 4.43-4.49 (m, 3H), 4.67 (dd, 1H, J = 7.9, 2.5 Hz), 4.75 (s, 2H), 5.60 (d, 1H, J = 5.0 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 24.6, 25.1, 26.2, 26.6, 39.0, 39.4, 64.1, 66.0, 70.5, 70.8, 71.2, 73.1, 76.2 (5C), 80.5, 96.5, 108.9, 109.7, 168.8; $[\alpha]_D$ = -36 (CH_2Cl_2, c = 0.67, 20 °C).

4.8.5. (1*R*,2*S*)-2-[*N*-(*tert*-Butoxycarbonyl)-*N*-methylamino]-1-phenylpropyl 2-iodoferrocenecarboxylate (diastereoisomeric mixture) (7f) was prepared from **6f** (1.9 g) and was isolated (eluent: 8:2 heptane-EtOAc) as a yellow oil (yield: 84%): ^{1}H NMR (500 MHz, 340 K, C_6D_6) δ common signals: 1.27 (d, 3H, J = 6.8 Hz), 1.34 (s, 9H), 2.57 (br s, 3H), 4.77 (br s, 1H), 7.08-7.20 (m,

3H); major diastereoisomer signals: 3.87 (s, 5H), 3.99 (t, 1H, *J* = 2.6 Hz), 4.42 (dd, 1H, *J* = 2.6, 1.6 Hz), 4.73 (dd, 1H, *J* = 2.6, 1.6 Hz), 6.21 (d, 1H, *J* = 8.6 Hz), 7.55 (d, 2H, *J* = 6.8 Hz); minor diastereoisomer signals: 3.86 (s, 5H), 3.98 (t, 1H, *J* = 2.6 Hz), 4.41 (dd, 1H, *J* = 2.6, 1.6 Hz), 4.82 (dd, 1H, *J* = 2.6, 1.6 Hz), 6.30 (d, 1H, *J* = 8.4 Hz), 7.66 (d, 2H, *J* = 7.2 Hz); ^{13}C NMR (125 MHz, 340 K, C_6D_6) δ common signals: 14.9, 28.5 (3C), 55.2, 72.0, 72.9 (5C), 79.2, 127.8-128.8 (5C), 139.5, 155.2; major diastereoisomer signals: 30.2, 39.9, 70.7, 72.3, 77.8, 80.2, 168.5; minor diastereoisomer signals: 30.3, 39.8, 71.3, 72.5, 78.4, 80.4, 168.8. Anal. Calcd for $C_{26}H_{30}FeINO_4$ (603.27): C, 51.76; H, 5.01; N, 2.32. Found: C, 52.09; H, 5.17; N, 2.27. Treatment with DIBAL-H according to **4.7. (b)** afforded 2-iodoferrocenemethanol (**9**) in 93% yield and 30% ee (S_P). **(1*R*,2*S*)-2-[*N*-(*tert*-Butoxycarbonyl)-*N*-methylamino]-1-phenylpropyl 2,5-diiodoferrocenecarboxylate (8f)** was isolated similarly in 9% yield as a yellow oil, and was identified by NMR: ^{1}H NMR (500 MHz, 340 K, C_6D_6) δ 1.35 (s, 9H), 1.38 (d, 3H, *J* = 6.8 Hz), 2.57 (br s, 3H), 3.86 (s, 5H), 4.34 (m, 2H), 4.98 (br s, 1H), 6.28 (d, 1H, *J* = 9.2 Hz), 7.09 (t, 1H, *J* = 7.6 Hz), 7.19 (t, 2H, *J* = 7.6 Hz), 7.70 (d, 2H, *J* = 7.6 Hz); ^{13}C NMR (125 MHz, 340 K, C_6D_6) δ 15.5, 28.5 (3C), 30.2, 39.0, 39.6, 55.0, 73.0, 75.9 (5C), 79.0, 79.2, 81.2, 81.2, 127.5-128.8 (5C), 139.1, 155.2, 167.2; $[\alpha]_D$ = +37.5 (CH_2Cl_2, *c* = 0.93, 20 °C).

4.8.6. 5-(*tert*-Butoxycarbonylamino)-5-deoxy-3-*O*-(2-iodoferrocenecarbonyl)-1,2-*O*-isopropylidene-α-D-xylofuranose (diastereoisomeric mixture) (7m) was prepared similarly from **6m** (2.0 g) but after treatment of the substrate with BuLi (1.6 M hexane solution, 4.0 mmol), and was isolated (eluent: 96:4 to 90:10 heptane-EtOAc) as an orange solid (yield: 48%). A 52% de was estimated by NMR. The analyses were as described previously.[15] Treatment with DIBAL-H according to **4.7. (b)** afforded 2-iodoferrocenemethanol (**9**) in 94% yield and 40% ee (S_P).

4.9. General procedure for the deprotonation using the lithium-zinc base prepared from $ZnCl_2$·TMEDA (1 equiv) and Li(TMP) (3 equiv) in THF followed by trapping using I_2. To a stirred cooled (0 °C) solution of 2,2,6,6-tetramethylpiperidine (1.1 mL, 6.0 mmol) in THF (5 mL) were successively added BuLi (1.6 M hexanes solution, 6.0 mmol) and, 5 min later, $ZnCl_2$·TMEDA[7e] (0.51

g, 2.0 mmol). The mixture was stirred for 10 min at 0 °C before introduction of the required substrate (2.0 mmol). After 2 h at room temperature, a solution of I_2 (1.5 g, 6.0 mmol) in THF (5 mL) was added. The mixture was stirred overnight before addition of an aq saturated solution of $Na_2S_2O_3$ (10 mL) and extraction with EtOAc (3 x 20 mL). After drying over anhydrous Na_2SO_4, the solvent was evaporated under reduced pressure, and the iodide was isolated by purification by flash chromatography on silica gel.

4.9.1. (2*S*,4*R*)-1-*tert*-Butoxycarbonyl-2-(*tert*-butyldiphenylsilyloxymethyl)-4-pyrrolidyl 2-iodoferrocenecarboxylate (diastereoisomeric mixture) (7g) was prepared from **6g** (1.3 g) and was isolated (eluent: 95:5 heptane-EtOAc) as an orange gum (yield: 73%): ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.05 (s, 9H), 1.34 and 1.46 (s, 9H), 2.21-2.59 (m, 2H), 3.57-3.86 (m, 3H), 3.98-4.25 (m, 2H), 4.21 and 4.22 (s, 5H), 4.44-4.46 (m, 1H), 4.69 (br s, 1H), 4.82-4.89 (m, 1H), 5.50-5.52 (m, 1H), 7.35-7.43 (m, 6H), 7.63-7.67 (m, 4H); HRMS: calcd for $C_{37}H_{44}{}^{56}FeINNaO_5Si$ $[(M+Na)^{+\bullet}]$ 816.1275, found 816.1276. Treatment with DIBAL-H according to **4.7. (b)** afforded 2-iodoferrocenemethanol (**9**) in 94% yield and 33% ee (S_P).

4.9.2. 3-*O*-(2-Iodoferrocenecarbonyl)-5-*O*-(*tert*-butyldiphenylsilyl)-1,2-*O*-isopropylidene-α-D-xylofuranose (diastereoisomeric mixture) (7h) was prepared from **6h** (1.3 g) and was isolated (eluent: 93:7 heptane-EtOAc) as an orange solid (yield: 86%). A 20% de was estimated by NMR. The analyses were as described previously.[15] Treatment with DIBAL-H according to **4.7. (b)** afforded 2-iodoferrocenemethanol (**9**) in 61% yield and 22% ee (R_P).

4.10. 1-*O*-(2-Iodoferrocenecarbonyl)-2,3:5,6-di-*O*-cyclohexylidene-α-D-mannofuranose (diastereoisomeric mixture) (7i). To a stirred cooled (0 °C) solution of 2,2,6,6-tetramethylpiperidine (1.1 mL, 6.0 mmol) in THF (5 mL) were successively added BuLi (1.6 M hexanes solution, 6.0 mmol) and, 5 min later, $CdCl_2$·TMEDA[36] (0.60 g, 2.0 mmol). The mixture was stirred for 10 min at 0 °C before introduction of **6i** (1.1 g, 1.3 mmol). After 2 h at room temperature, a solution of I_2 (1.5 g, 6.0 mmol) in THF (5 mL) was added. The mixture was stirred overnight before addition of an aq saturated

solution of $Na_2S_2O_3$ (10 mL) and extraction with EtOAc (3 x 20 mL). After drying over anhydrous Na_2SO_4, the solvent was evaporated under reduced pressure, and the iodide **7i** was purified by purification by flash chromatography on silica gel. Compound **7i** could not be separated from the starting material (estimated yield: 67%). A 48% de was estimated by NMR. The analyses were as described previously.[15] The treatment of a fraction containing only the main diastereoisomer with DIBAL-H according to **4.7. (b)** afforded (S_P)-2-iodoferrocenemethanol (**(S_P)-9**).

4.11. 3-*O*-(2-Iodoferrocenecarbonyl)-1,2:5,6-di-*O*-isopropylidene-α-D-glucofuranose (diastereoisomeric mixture) (7j). To a stirred cooled (0 °C) solution of 2,2,6,6-tetramethylpiperidine (1.1 mL, 6.0 mmol) in THF (5 mL) was added BuLi (1.6 M hexanes solution, 6.0 mmol). After 5 min, this solution was transferred at -10 °C to $CdCl_2$ (0.37 g, 2.0 mmol) dried by heating under vacuum. The mixture was stirred for 10 min at 0 °C before introduction of **6j** (0.94 g, 2.0 mmol). After 2 h at room temperature, a solution of I_2 (1.5 g, 6.0 mmol) in THF (5 mL) was added. The mixture was stirred overnight before addition of an aq saturated solution of $Na_2S_2O_3$ (10 mL) and extraction with EtOAc (3 x 20 mL). After drying over anhydrous Na_2SO_4, the solvent was evaporated under reduced pressure, and the iodide **7j** was isolated by purification by flash chromatography on silica gel. It was isolated (eluent: 93:7 heptane-EtOAc) in 87% yield. A 82% de was determined by NMR. The analyses of both diastereoisomers were as described previously.[15] The treatment of a fraction containing only the (R_P)-diastereoisomer with DIBAL-H according to **4.7. (b)** afforded (R_P)-2-iodoferrocenemethanol (**(R_P)-9**) in 93% yield. The treatment of a fraction containing only the (S_P)-diastereoisomer with DIBAL-H according to **4.7. (b)** afforded (S_P)-2-iodoferrocenemethanol (**(S_P)-9**) in 95% yield.

4.12. (R_P)-6-(*tert*-Butoxycarbonylamino)-6-deoxy-5-*O*-(2-iodoferrocenecarbonyl)-1,2-*O*-isopropylidene-3-*O*-methyl-α-D-glucofuranose (R_P-7n). To a stirred cooled (0 °C) solution of 2,2,6,6-tetramethylpiperidine (0.68 mL, 4.0 mmol) in THF (5 mL) was added BuLi (1.6 M hexanes solution, 4.0 mmol). After 5 min, the solution was cooled at -10 °C and added to $ZnCl_2$ (0.27 g, 2.0 mmol). The mixture was stirred for 10 min at 0 °C and transferred to **6n** (1.1 g, 2.0 mmol) in THF (5

mL). After 10 min at room temperature, a cooled (-30 °C) solution prepared in THF (5 mL) from 2,2,6,6-tetramethylpiperidine (0.68 mL, 4.0 mmol) and BuLi (1.6 M hexanes solution, 4.0 mmol) was added, and the resulting mixture was stirred for 2 h at room temperature before a solution of I_2 (2.0 g, 8.0 mmol) in THF (5 mL) was added. The mixture was stirred overnight before addition of an aq saturated solution of $Na_2S_2O_3$ (10 mL) and extraction with EtOAc (3 x 20 mL). After drying over anhydrous Na_2SO_4, the solvent was evaporated under reduced pressure, and the iodide ***R*$_P$-7n** was isolated by purification by flash chromatography on silica gel. It was isolated (eluent: 7:3 heptane-EtOAc) as an orange gum (yield: 57%). The analyses were as described previously.[15]

4.13. *Meso*-2,2"-Bis(methoxycarbonyl)-1,1"-biferrocene (*meso*-10o) was synthesized by adapting a described procedure.[27] Treating under argon a solution of racemic methyl 2-iodoferrocenecarboxylate (***rac*-7o**, 0.72 g, 2.0 mmol) in toluene (15 mL) by NaH (60% in a mineral oil, 0.64 g, 16 mmol), $NiCl_2(PPh_3)_2$ (1.3 g, 2.0 mmol), PPh_3 (1.0 g, 4 mmol), and Zn (powder, 0.52 g, 8.0 mmol) resulted in a mixture that was heated at 75 °C for 12 h. Quenching at room temperature with 5% HCl, extraction with Et_2O (2 x 10 mL) and CH_2Cl_2 (10 mL), washing of the combined organic layers with brine (2 x 10 mL), drying over Na_2SO_4, and purification by flash chromatography on silica gel (eluent: 9:1 heptane-EtOAc) afforded ***meso*-10o** as an orange solid (yield: 53%): mp 159 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.81 (s, 6H), 4.07 (s, 10H), 4.43 (t, 2H, J = 2.6 Hz), 4.82 (dd, 2H, J = 1.6, 2.6 Hz), 4.99 (dd, 2H, J = 1.6, 2.6 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 51.6 (2C), 69.5 (2C), 69.6 (2C), 70.4 (2C), 71.5 (10C), 76.9 (2C), 85.6 (2C), 172.0 (2C); HRMS: calcd for $C_{24}H_{22}{}^{56}Fe_2NaO_4$ $[(M+Na)^{+\bullet}]$ 509.0109 and $C_{24}H_{22}{}^{56}Fe_2O_4$ ($M^{+\bullet}$) 486.0211, found 509.0110 and 486.0231. The structure of ***meso*-10o** was identified unequivocally by X-ray structure analysis (CCDC 970488) from crystals obtained by slowly evaporating a 7:3 hexane-CH_2Cl_2 solution. **2,2"-Bis(methoxycarbonyl)-1,1"-biferrocene (racemic mixture) (*rac*-10'o)** was obtained similarly (eluent: 7:3 heptane-EtOAc) as an orange solid (yield: 15%): mp 185 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 3.62 (s, 6H), 4.20 (s, 10H), 4.45 (t, 2H, J = 2.6 Hz), 4.83-4.81 (m, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 51.3 (2C), 69.1 (2C), 70.0 (2C), 71.0 (10C), 71.7

(2C), 76.4 (2C), 85.1 (2C), 172.0 (2C); HRMS: calcd for $C_{24}H_{22}{}^{56}Fe_2NaO_4$ [$(M+Na)^{+\bullet}$] 509.0109 and $C_{24}H_{22}{}^{56}Fe_2O_4$ ($M^{+\bullet}$) 486.0211, found 509.0110 and 486.0213. The structure of ***rac*-10'o** was identified unequivocally by X-ray structure analysis (CCDC 970489) from crystals obtained by slowly evaporating a 7:3 hexane-CH_2Cl_2 solution.

4.14. General procedure for the Suzuki coupling. A solution of the required iodoferrocene **7** (0.5 mmol), the required boronic acid (2.0 mmol), and CsF (0.15 g, 1.0 mmol) in the toluene (5 mL) was degassed with Ar for 30 min before addition of $Pd(dba)_2$ (14 mg, 25 μmol), and PPh_3 (26 mg, 0.10 mmol). The resulting mixture was heated for 12 h under reflux before cooling and dilution with Et_2O (30 mL), washing with H_2O, and extraction with CH_2Cl_2 (3 x 20 mL). After drying over anhydrous Na_2SO_4, the solvent was evaporated under reduced pressure, and the iodide was isolated by purification by flash chromatography on silica gel.

4.14.1. Methyl 2-(4-methoxyphenyl)ferrocenecarboxylate (racemic mixture) (*rac*-11o) was prepared from racemic methyl 2-iodoferrocenecarboxylate (***rac*-7o**, 0.18 g) and 4-methoxyphenylboronic acid (0.30 g). It was isolated (eluent: 93:7 heptane-EtOAc) as an orange gum (yield: 97%): ^{1}H NMR (300 MHz, $CDCl_3$) δ 3.76 (s, 3H), 3.83 (s, 3H), 4.20 (s, 5H), 4.45 (t, 1H, J = 2.6 Hz), 4.56 (dd, 1H, J = 1.6, 2.5 Hz), 4.88 (dd, 1H, J = 1.6, 2.6 Hz), 6.87 (d, 2H, J = 8.8 Hz), 7.55 (d, 2H, J = 8.8 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 51.2, 55.0, 68.3, 69.5, 70.9 (5C), 71.1, 73.7, 90.8, 112.6 (2C), 128.6, 131.1 (2C), 158.4, 171.7; HRMS: calcd for $C_{19}H_{18}{}^{56}FeNaO_3$ [$(M+Na)^{+\bullet}$] 373.0503, found 373.0500.

4.14.2. (R_P)-3-*O*-(2-(4-Methoxyphenyl)ferrocenecarbonyl)-1,2:5,6-di-*O*-isopropylidene-α-D-glucofuranose (R_P-11j) was prepared from ***S*$_P$-7j** (0.30 g) and 4-methoxyphenylboronic acid (0.30 g). It was isolated (eluent: 93:7 heptane-EtOAc) as an orange gum (yield: 98%): ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.28 (s, 3H), 1.33 (s, 3H), 1.43 (s, 3H), 1.53 (s, 3H), 3.83 (s, 3H), 4.07-4.28 (m, 4H), 4.26 (s, 5H), 4.48 (t, 1H, J = 2.6 Hz), 4.54 (d, 1H, J = 3.6 Hz), 4.61 (dd, 1H, J = 1.6, 2.6 Hz), 4.88 (dd, 1H, J = 1.6, 2.6 Hz), 5.38 (d, 1H, J = 2.8 Hz), 5.86 (d, 1H, J = 3.6 Hz), 6.87 (d, 2H, J = 8.8 Hz), 7.58 (d, 2H, J = 8.8

Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 25.3, 26.1, 26.7, 27.0, 55.2, 67.1, 67.5, 70.0, 71.2 (5C), 72.3, 74.2, 75.5, 80.1, 83.3, 91.4, 105.1, 109.5, 112.2, 112.8 (2C), 128.3, 131.4 (2C), 158.7, 170.1; $[\alpha]_D$ = -13.7 ($CHCl_3$, *c* = 2.4, 20 °C); HRMS: calcd for $C_{30}H_{34}{}^{56}FeNaO_8$ $[(M+Na)^{+\bullet}]$ 601.1495, found 601.1493.

4.14.3. (*S*$_P$)-6-(*tert*-Butoxycarbonylamino)-6-deoxy-5-*O*-[2-(4-methoxyphenyl)ferrocenecarbonyl]-1,2-*O*-isopropylidene-3-*O*-methyl-α-D-glucofuranose (*S*$_P$-11n) was prepared from ***R*$_P$-7n** (0.34 g) and 4-methoxyphenylboronic acid (0.30 g). It was isolated (eluent: 8:2 heptane-EtOAc) as an orange gum (yield: 96%): ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.31 (s, 3H), 1.42 (s, 9H), 1.49 (s, 3H), 3.32 (s, 3H), 3.44 (dt, 1H, *J* = 6.2, 12.5 Hz), 3.65 (d, 1H, *J* = 3.6 Hz), 3.74 (ddd, 1H, *J* = 4.0, 5.8, 14.2 Hz), 3.82 (s, 3H), 4.20-4.26 (m, 1H), 4.24 (s, 5H), 4.46 (t, 1H, *J* = 2.5 Hz), 4.53 (d, 1H, *J* = 3.7 Hz), 4.56 (dd, 1H, *J* = 1.6, 2.5 Hz), 4.87-4.96 (m, 2H), 5.19-5.25 (m, 1H), 5.88 (d, 1H, *J* = 3.7 Hz), 6.86 (d, 2H, *J* = 8.8 Hz), 7.54 (d, 2H, *J* = 8.8 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 26.2, 26.7, 28.4 (3C), 42.0, 55.2, 57.8, 67.9, 69.2, 69.8, 71.0, 71.2 (5C), 74.1, 79.1, 79.9, 81.0, 83.7, 91.4, 105.0, 111.7, 112.8 (2C), 128.6, 131.3, 155.7, 158.6, 170.6; $[\alpha]_D$ = +3.93 ($CHCl_3$, *c* = 1.6, 20 °C); HRMS: calcd for $C_{33}H_{41}{}^{56}FeNNaO_9$ $[(M+Na)^{+\bullet}]$ 601.1495, found 601.1493.

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Supplementary data. CIF files and X-ray crystallographic data for **2c**, **6c-e, 6i-l, *meso*-10o** and ***rac*-10'o**. NMR spectra for **2c**, **5g**, **6a-c**, **6f,g**, **7a,b,f,g**, **8a,d-f,n**, ***meso*-10o**, ***rac*-10'o**, ***R*$_P$-11j**, ***S*$_P$-11n** and ***rac*-11o**. These data can be found in the online version, at http://dx.doi.org/10.1016/j.tet.xxxxxxxxxxx.

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